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ARTICLE

A New Approach of Intelligent Data Retrieval Paradigm

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ABSTRACT

What is a real time agent, how does it remedy ongoing daily frustrations for users, and how does it improve the retrieval performance in World Wide Web? These are the main question we focus on this manuscript. In many distributed information retrieval systems, information in agents should be ranked based on a combination of multiple criteria. Linear combination of ranks has been the dominant approach due to its simplicity and effectiveness. Such a combination scheme in distributed infrastructure requires that the ranks in resources or agents are comparable to each other before combined. The main challenge is transforming the raw rank values of different criteria appropriately to make them comparable before any combination. Different ways for ranking agents make this strategy difficult. In this research, we will demonstrate how to rank Web documents based on resource-provided information how to combine several resources raking schemas in one time. The proposed system was implemented specifically in data provided by agents to create a comparable combination for different attributes. The proposed approach was tested on the queries provided by Text Retrieval Conference (TREC). Experimental results showed that our approach is effective and robust compared with offline search platforms.

1. Introduction

With the growing number of information sources available via the internet, the problem of how to combine distributed and heterogeneous information sources is becoming increasingly difficult [1]. Large area, high bandwidth network such as World Wide Web creates a number of opportunities and challenges for effective retrieval of information. Such a network makes users to gain access to huge amounts of data in a wide variety of types. In realistic setting, without effective information management tools most of this data are worthless since users are unable to find data of interest [6,7]. Currently, the available source of information in World Wide Web is classified domains into particular topics, including: health, travel, shopping, etc. The classical contents, such as: URL, title, headers, and document body; as well as the traditional ranking, such as: global rank, local rank, insight rank, knowledge bases rank, and so forth are important contents making information distributed resources in agents are comparable. In recent years, traditional approaches to building distributed or aggregated systems do not scale well [5]. Current systems e.g. search engines or topic directories on the World Wide Web provide limited capabilities for locating, combining, processing, and organizing information. The advent of large area networks connecting

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many diverse repositories of data creates the challenge of finding particular data of interest easily and timely manner. More contrast, providing access to the large number of information sources and organizing them into a network of information agents is a big challenge. Each agent provides expertise on a specific topic and sometimes drawing on relevant information from other information agents. To build such topographical network, we need an infrastructure of a single agent system that can be instantiated to provide accessing to multiple agents. Information mediator that provides access to heterogeneous data and knowledge base is an aspect of our previous work \[9\]. We need to consider a unique aspect that is critical for any agent-based system: how to draw and simulate knowledge in the network and how to categorize or classify data in the network based on their topic similarity; and finally how to combine them. Formulating the results retrieved from distributed agents and computing the federated rank based on that aspect is the last goal of our approach.

However, the standard form of searching topics in the network is to use vector space model and inner product for similarity \[2\]. The inner product syntax composed of atoms that retrieve documents from index file, and inner operators work on their operands to retrieve set of documents that compromise a set of vectors. On another hand, keywords in a query can be expressed in a syntax tree where leaves are the basic query keywords and the internal nodes are the operators. The operators that commonly used in inner expression could select documents satisfying different features. Besides selecting the appropriate documents based on particular features, the retrieval approach might also add other criteria to enhance the initial rank if some similar features detected in some documents in similar resources. To provide an efficient information retrieval approach in large distributed resources, it is important to process resources and commonly build a desired index \[10\]. Realistically, the professional and significant prototype of index structure in the distributed agents is a memory allocation table or so-called ‘hash table’, which is a data structure that stores data in an associative manner. Data is stored in an array format, where each data value has its own unique index value. Access of data becomes very fast if we know the index of the desired data. In turn, search system collects, parses, and stores data in the hash content in order to facilitate the process of fast indexing and retrieving.

The rest of this manuscript is organized as follows: Section 2 will outline some related work. Section 3 will discuss the architecture of our proposed approach. Section 4 will demonstrate the query processing and documents ranking procedure. Result analysis will be discussed in Section 5, while Section 6 will outline the comparison between our proposal and some related work. Experimental results and interface will be discussed in Section 7, and finally, conclusions are highlighted in Section 8.

2. Related Work

With the vast amount of information resources available today, a crucial problem is how to locate, retrieve and process information in that resources. It would be impractical to build a single unified system that combines all of these information resources. A more promising approach compromises between agents in a network of information retrieval agents when needed. There has been much recent work in a similar vein where the aim is to build a distributed index that share different tasks. Researchers \[9\] proposed an automated image information retrieval system that helped internet users to find the required information with high performance. Experiments showed that gathering images potentially takes a long time with a single-threaded information crawler on a single computer. Deploying parallel information crawler and distributed across many machines was addressed that problem. Another researcher \[9\] attempts to use a thesaurus to provide meaningful search of the query to help the distributed model to utilize for document retrieval. A scalable agent-based information retrieval engine \[10\] deployed intelligent software agents, natural language understanding, and conceptual search techniques to support public accessing to the data over the distributed resources. The researcher had demonstrated the feasibility of multi-agent architecture to support intelligent information accessing and retrieving. A so-called “just-in-time” information retrieval agent \[11\] was another model that proactively retrieves and presents information based on a person’s local context. Researchers showed that users of agents are not merely more efficient at retrieving information, but actually retrieve and use more information than they would with traditional search engines. Multi-agent information retrieval system based on ontology was proposed by researchers \[12\]. They proposed a multi-agent information retrieval system based on ontology. Researchers showed that introducing ontology on information retrieval system can realize knowledge domain-expression in order to provide users with the increment of information service and refine the initial query.

3. Components of the Proposed Approach

In this section, we describe the key components of our proposed information retrieval model. As the number of documents that represents the relevant content in our distributed resources has increased, the system for searching relevant documents for each query is
needed and must be built efficiently. We will discuss our documents indexing algorithm in each agent represented by local indexes connected by a centralized index. It is worth mentioning that the key note for rebuilding index table is only when a new set of documents is added to the collection or when there is substantial changing in the data. In this section we will describe our key components of our proposal approach, as shown in Figure 1.

Figure 1. The architecture of our distributed model

3.1 Distributed Indexes

According to the requirements of distributed agents, centralized index in each agent normally gathers documents from the distributed resources devoted similar topic. The information in remote documents returned to a searcher implies two types of data: Meta and regular. We aimed to work with the textual information as text fields in a hash table format in order to allow more flexible indexing and retrieving. Some textual indexing format has limited matching capabilities. Hash table emphasizes simplicity, generality, and usability across our distributed resources. Although the design of hash table focuses on limited capabilities, it is widely used for the representation of arbitrary data structures; such as those used in web services. Data is strongly structured and stored in hash table and text is quite restrictive [13]. Our document representations have a fixed set of attributes; some fields are textual content while others are not. The attributes are in a fixed order in documents; such that, if document does not contain enough text, it does not classify under any attribute because attributes are not allowed to be nested or overlapped. As a result, the retrieval data restricted to specifying that giving basic evidence is only for a given attribute. This is more reasonable when collection has a fixed structure e.g. indexing meta-data without tokenization. As shown in the example below, data is structured into many attributes and evidences. Each set is for an identical agent; and thus, set of resources with similar task are aggregated in indexing file.

Currently, we have approximately of 24 agents and different number of resources for each, as shown in Table 1, each resource in agent advert some searchable parameters grouped in similar task. The principle for categorizing agents and how tasks involved for each were mentioned in [4].

Table 1. Agents categories and number of resources used for each

| Agents           | Topics |
|------------------|--------|
| Indeed.co.uk     | Jobs   |
| Totaljobs.com    | Jobs   |
| Optnation.com    | Jobs   |
| Monster.co.uk    | Jobs   |
| Wikicfp.com      | Academic |
| Dblp.org         | Academic |
| Citeseer.edu     | Academic |
| Univerzities.com | Academic |
| Conferencealert.com | Academic |
| Researchgate.com | Academic |
| Taste.com        | Recipes |
| Simplerecipes.com | Recipes |
| Saveland.ca      | Shopping |
| Amazon.com       | Shopping |
| Ebay.com         | Shopping |
| Alibaba.com      | Shopping |
| Answers.com      | Q/A    |
| Answers.yahoo.com | Q/A   |
| Wikihow.com      | Q/A    |
| Drugs.com        | Health |
| Everydayhealth.com | Health |
| Nhs.uk           | Health |
| Patient.info     | Health |
| dermat101.com    | Health |
| Citravel.com     | Health |
| Hotelscombined.com | Travel |
| Tripsavvy.com    | Travel |
| Trygside.com     | Shows  |
| Hollywoodlife.com | Shows |
| Imdb.com         | Shows  |
| Thespruce.com    | Home   |
| Investopedia.com | Local  |
| Mapquest.com     | Local  |
| Embassypages.com | Local  |
| Zoominfo.com     | Local  |
| Foursquare.com   | Weather |
| Openweathermap.org | Encyclopedia |
| Wikipedia.org    | Encyclopedia |
| Nationsonline.com | Encyclopedia |
| Gov.uk           | Encyclopedia |
| Geonames.org     | Encyclopedia |
| Nationsonline.org | Encyclopedia |
| Reference.com    | Encyclopedia |
| Thoughtco.com    | Encyclopedia |
| NPR.org          | News   |
| News-medical.net | Health |
| Uptodate.com     | Health |
| Verywell.com     | Health |
| Mayoclinic.org   | Finance |
| Thebalance.com   | Finance |
| Historynet.com   | History |
| Twitter.com      | Social |
| Facebook.com     | Social |
| Wordpress.com    | Blog   |
| Thefreedictionary.com | Dictionary |
| Merriam-webster.com | Dictionary |
| Cambridge.org    | Dictionary |
| Google.com       | Scholar |
| Worddat.org      | Scholar |
| 360daily.com     | Video  |
| Vimeo.com        | Video  |

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3.1.1 Features Selection

We need to extract some features (attributes) from resources to be evaluated in a heuristic search, and to provide a basis for the learning component. The most promising schema uses vector space information retrieval paradigm, where documents are represented as vectors [2]. In our paradigm, we use features that are related to the resources that devoted locally and globally. As a result, each set of similar resources is specifically located to a topical agent. Below is an example of a document retrieved from a resource “drug.com” corresponding to an agent “Health”. The features we proposed are: “URL”, “title”, “snippet”, “IDF”, “PageRank”, “Global Rating”, “Local Rating”, “date”, “time”, and “home”. The example below shows the proposed attributes and the corresponding values.

| Agent: Health; |
|----------------|
| Resource: drug.com; |
| URL: http://www.drugs.com/cg/lipoma.html; |
| Title: “Lipoma » What You Need to Know”; |
| Snippet: “A lipoma is a benign (non cancer) tumor made up of fat tissue. Lipomas can form anywhere in your body, but are usually found on the back, shoulders, neck, and head. The cause of lipomas is unknown. Some types of lipomas may run in families”.

\[
IDF = 0.7;
PageRank = 0.4;
Wiki = 1;
Agent = 0.3;
Resource = 0.7;
Home = 1;
Expiration = 1-15 second;
Type: info, video, image, social, link, web, article;
\]

3.1.2 Features Weighting

The proposed schematic weights in our algorithm are influenced from our previous experiments using eight schematic weights: (1) ‘URL’, ‘title’, and ‘snippets’ are attributes used to force a high impact weight for document relevancy. We assume that query terms in ‘snippets’ are more scattered than in ‘URL’ and in ‘title’; in which, we assigned a maximum weight as 0.2, 0.1, 0.1 to URL, title, snippets, respectively. (2) The PageRank attribute plays a significant algorithm for moving the relevant pages on the top of the result list [25-27]. The Alexa networking was used to collect PageRank data for each domain. (3) The Inverse Document Frequency (IDF) emphasis on the number of documents involved in each resource that contains similar query terms, the value is computed as follows:

\[
IDF_k = \log_2 \frac{n}{d_k}
\]

where \(d_k\) denotes the document frequency of term \(k\), where as \(n\) denotes the number of documents in the collection.

(4) The ‘Local Ranking in Agent” and “Local Ranking in Resource” attributes assume that at most we retrieve 10 resources from each agent and 10 documents from each resource. Therefore, if a document retrieved from an agent \(n\) and a resource \(m\), the rank is \(n+m\). Experimentally, we ordered resources in an agent based on the user’s preferences. (5) In terms of the ‘Wikipedia’ attribute, our perspective is that not all terms involved in the ‘URL’ are labeled as domain-specific terms unless they shared with the Wikipedia content. For instance, if documents retrieved from a particular resource and such document is referenced by Wikipedia, the documents will be ranked high “0.10”; otherwise “0.0”. (6) The Date attribute is used to give a high weight for a document that created recently in its resource, in which, 0.05 is assigned for document has been created at the moment, e.g. publicizing a link to such document in Twitter or news websites. (7) Similarly, if a document is referenced in a home-page, it will be ranked high in a “Home” attribute; the order of its link in the home page will determine the value of relevancy. That means, the first document is ranked “0.5” and the second document is ranked “0.4”, and so on. (7) The “Expiration” attribute is parametric rather than metric; which means, if an agent retrieves a document from a resource within the expiry time, the document will be declined unless the search process is still active and the number of returning documents is still few. (8) Likewise, “Type” attribute is used for categorizing the results on the user’s frontend. Means, assigns high priority to the results returning from Twitter, Wikipedia and so on. The following table shows the types of features and the schematic weighting at each one.
This process is commonly referred to gripping through a structured form of hash table to scan the index linearly. [3]

Attributes, the index table is dispersed a bit in its content. Because not all documents in an agent satisfy all attributes, as mentioned in the previous section. One way to overcome this problem is to ensure that the index table is quite small, the index built instantly in the memory instead of in the disk space. This is why we composed the index table into a fixed schematic value of ranking for agents. The indexer assigned a static value for an attribute in the document. We proposed a fixed schematic value of ranking for attributes presented in the documents as well as in its agents, including the highest rank if all query terms are available and the lowest if otherwise. [7]

Often, indexing model shares similar document statistics with other models when data derived from different relevance matching assumptions. The indexer distills information in the corpus of documents in the network into a format that is suitable for quick access by the query processor. This typically extracting document features by breaking documents down to their constituent terms, as well as extracting any statistics related to the terms in the documents of related resources, and then calculating any query related evidences represented in its attributes, as mentioned in the previous section.

Our agent-based search architecture comprises three types of local agents: dispatch, display, and search engine interface. These agents are type of Web-accessible services; and in turn, agents communicate with each other to process the required task. The purpose of the interface agents is to facilitate and incorporate a variety of search services; whereas, each interface agent is designed to accommodate its target remote agents and failure modes. However, all these principal components are stimulated and controlled by a query processor which, in turn, deployed for document ranking to compute the degree of document relevancy. [10]

Then a ranking list is produced by sorting in descending order of the relevance score. Generally, the ranking schema incorporates one of two types of evidences: dynamic or static. Dynamic ranking exploits the heuristic forms of document evidences; whereas in static, ranking assigns a particular value for the evidence. As we experienced earlier in our previous approaches, we assigned a static value for an attribute in the document. We proposed a fixed schematic value of ranking for attributes presented in the documents as well as in its agents. [10]

More contrast, given query ‘Q’ composites from three terms, the first step is to search those terms in the index file in resource ‘R’ in an agent ‘A’. The

### Table 2. Features, types, and ranking schema

| Attribute | Weight |
|-----------|--------|
| URL       | 0.0 - 0.20 |
| Title     | 0.0 - 0.10 |
| Snippet   | 0.0 - 0.10 |
| PageRank  | 0.0 - 0.10 |
| Inverse Document Frequency (IDF) | 0.0 - 0.10 |
| Local Ranking in Agent | 1.0 - 0.10 |
| Local Ranking in Resource | 0.0 - 0.10 |
| Wikipedia | 0 or 0.10 |
| Expiration | 0.0 - 0.05 |
| Type      | 0.0 - 0.05 |

### 3.2 Centralized Index

Often, indexing model shares similar document statistics with other models when data derived from different relevance matching assumptions. The indexer distills information in the corpus of documents in the network into a format that is suitable for quick access by the query processor. This typically extracting document features by breaking documents down to their constituent terms, as well as extracting any statistics related to the terms in the documents of related resources, and then calculating any query related evidences represented in its attributes, as mentioned in the previous section.

As our approach runs in real-time and the proposal index table is quite small, the index built instantly in the memory instead of in the disk space, for the following reasons:

1. To overcome the problem of disk overhead.
2. To avoid the network delay, accessing the index through the internet for every query searching is fairly expensive to the users.
3. Accessing the data in the memory is mostly 10 times faster than any other medium.

Using the index can only determine whether searching string exists in a particular document or not. Because the index stores information regarding the degree of matching and other attributes, it is therefore considered to be an informational and knowledgeable index. Such an index can be used to determine not only document matching a query, but also can be used to compute the rank of documents.

Because not all documents in an agent satisfy all attributes, the index table is dispersed a bit in its content. This is why we composited the index table into a structured form of hash table to scan the index linearly. This process is commonly referred to gripping through text. Gripping linearly through the text can be very effective process, especially influences the speed of modern computers. Depending on whether we look at the table rows (documents) or table columns (attributes) we can have a vector for each attribute or a vector for each document.

\[ A_{Shopping} \xrightarrow{\text{R_i}} [...d_1...<d_2...>...<d_m...>]R_i[<d_1...<d_2...>...<d_m...>] \rightarrow ...R_n[<d_1...<d_2...>...<d_m...>] \]

### 4. Query Processing and Document Ranking

Intelligent retrieval systems are capable of understanding user intentions and use this knowledge in the information retrieval process. To support our intelligent retrieval model, advanced navigational techniques such as relevance ranking, natural language queries, and concept searching are required in evolving information retrieval systems.

Our agent-based search architecture comprises three types of local agents: dispatch, display, and search engine interface, while a set of distributed agents incorporated globally. In local agents, the interface agent uses REST API to communicate with remote global agents which are type of Web-accessible services; and in turn, agents communicate with each other to process the required task. The purpose of the interface agents is to facilitate and incorporate a variety of search services; whereas, each interface agent is designed to accommodate its target remote agents and failure modes. However, all these principal components are stimulated and controlled by a query processor which, in turn, deployed for document ranking to compute the degree of document relevancy. [10]
corresponding posting list of matched documents is fetched and transferred to another table in the memory. The posting ranks for all selected attributes are summed linearly to represent the initial rank for each document. Thereafter, the posting list of documents will be ordered in initial order, and in some cases, set of documents may incorporate equal ranks. Based on our ranking schema, if set of documents retrieved from set of resources and corporate equal ranks, it must be re-ranked again using user preferences, e.g. homepage, social pages, news, etc. The final results are merged in the forward table before displayed to the user. First of all, Jaccard Coefficient is used to compute the similarity between the user’s query ‘Q’ and document attributes (URL, title, snippets):

\[
\text{Similarity}(D, Q) = \sum i \frac{|D \cap Q|}{|D| + |Q| - |D \cap Q|}
\]

\[
= \frac{\sum a_i q_i}{\sum a_i^2 + \sum a_i q_i - \sum a_i q_i} \cdot N(a)
\]  

\[\text{(2)}\]

where \(n\) is the number of terms in the query (Q), \(N\) is a normalized value for an attribute \(a\). Then, the similarity weight is accumulated with the schematic weights of other attributes to represent the final rank of document \(D\), as shown below:

\[
\text{Rank}(D, Q) = \text{Similarity}(D, Q) + \sum a \text{Nomialize}(a) \cdot AE > 0.6
\]  

\[\text{(3)}\]

The pseudo code below shows the proposal ranking algorithm.

```plaintext
Initialize
Loop for each document ‘D’ in the collection;
C1→URL, title, snippet, C2→PageRank, Local, Wikipedia, IDF;
Loop for all attributes ‘t’ in document ‘D’;
If C1 and attribute ‘t’ = C1 then increment rank ‘R’ to document ‘D’ by C1;
Else if C1 and attribute ‘t’ ≠ C1 then assign rank ‘R’ to document ‘D’ by ‘0’;
if C2 and attribute ‘t’ = C2 then increment rank ‘R’ to document ‘D’ by C2;
End of loop for all attributes in document;
Forward document D and its rank in table ‘T’;
End of loop for each document in collection;
Sort documents in table ‘T’ Ascending;
Loop for all documents in table ‘T’;
Loop for each rank ‘R’ in table ‘T’;
Sort rank ‘R’ alphabetically;
End of loop for each rank;
End of loop for all documents;
Display result.
```

5. Result Analysis and Discussion

Though our model is for selecting the appropriate schematic rank for some attributes proposed by our model, specifying the relevant agent for a user query topic and deterring the appropriate resources in right order is the main goal for our approach. By submitting a preliminary run to this system, the runs were validated by checking if they adhere to the TREC format, and the main evaluation metrics were returned. The evaluation metrics returned were based on 10 test queries (fully annotated but not used for the actual evaluation). Figure 2, 3, and 4 showed the main evaluation metrics (F1\(^{(1)}\) for Agent Selection, and nDCG@5, nDCG@10, and nDCG@20 for both Resource Selection and Results Merging) for validating run among the online trial submissions. These metrics are the results with respect to the 50 evaluation topics, not including the 10 test topics for which the participants received the intermediate results (and towards which their systems might have been tuned). We often submitted consecutive runs to the model, either for a range of different techniques, e.g. ordering the resources in the agent using different schematic preferences, or maybe to determine suitable values for modeling hyper parameters. For the Agent Selection task, our approach has a substantial increasing in effectiveness over the systems submitted to TREC. For the Resource Selection task, we have a good improvement over other systems\(^{(4)}\). For the Results Merging task, we have better results over other systems. The test and training sets of queries involved for two tasks (Adhoc and Diversity) as well as some relevancy complexity. F-measure and Normalized Discounted Cumulative Gain (nDCG) are computed as follows:

\[F = \frac{2 \cdot \text{Precision} \cdot \text{Recall}}{\text{Precision} + \text{Recall}}\]  

\[\text{(4)}\]

The DCG accumulated at a particular rank position \(p\) \{'displaystyle p\} is defined as:

\[\text{DCG}_p = \sum_{i=1}^{p} \frac{\text{rel}_i}{\log_2(i+1)}\]  

\[\text{(5)}\]

The nDCG values for all queries can be averaged to obtain measure of the average performance of ranking algorithm. A perfect ranking algorithm, the \(\text{DCG}_p\) will be producing an \(n\text{DCG}\) of 1.0. All \(n\text{DCG}\) calculations are involved on the interval 0.0 to 1.0 cross-query comparable (Figure 2 and 3). Figure 4 and 5 are showed the accuracy of agent and resource selection, respectively; whereas Figure 6 shows the accuracy of result merging. Table 3 shows the Discounted Cumulative Gain for each attribute, in which, Wikipedia’s attribute is identical and comparable with others.

\(\text{1}^{(1)}\) Usually F-measure called F1 because recall and precision are evenly weighted.
6. Comparisons & Outlook

The best performing methods, as shown in the Table 4, rely on indices based on single documents (rather than snippets) and combine evidence from classical retrieval algorithms such as variations on TF.IDF and language modeling. The best running models did not use external resources such as Wordnet and Wikipedia, but we showed how Wikipedia was played a very important feature for enhancing overall performance. A notable exception was the RS_clue web baseline, which used the collections’ snippets in combination with the ClueWeb’09 collection to make size estimates.

We assume that for a given query all engine results are readily available but more realistic scenario would be to first make a selection of a small number of promising engines, and to retrieve and re-rank this set of results. As shown in the Table 4, the best run performed nDCG@20 score 0.439. The organizers’ baseline runs used the static rankings from the corresponding size-based resource selection baselines (RM_clueweb and RM_query pools). The results of the top 5 ranked resources were combined using a round-robin merge. In our perspective, querying the TREC FedWeb 2013 collection is different from such realistically created test collections, in which, it provides the real results of 157 real web search engines and each provides its own retrieval method and heterogeneous content types including images, PDF, plain-text, video, etc. Also, querying lots of resources e.g. 157 and selecting only 5 resources resulting network overload.
which was not applicable in the real-time algorithm. Appendix (A) shows the 50 test queries, whereas Appendix (B) shows the ClueWeb19 collection used by other models.

| Table 4. The performance of related approaches |
|-----------------------------------------------|
| **Group ID**         | **Run ID**  | **nDCG@20** |
|----------------------|-------------|-------------|
| CMU_LTI              | googTermWise7 | 0.286       |
|                      | googUniform7  | 0.285       |
|                      | plain        | 0.277       |
|                      | sdm5         | 0.276       |
| ECNUCS               | basedef     | 0.289       |
| ICTNET               | ICTNETR01    | 0.247       |
|                      | ICTNETR02    | 0.309       |
|                      | ICTNETR03    | 0.348       |
|                      | ICTNETR04    | 0.381       |
|                      | ICTNETR05    | 0.334       |
|                      | ICTNETR06    | 0.402       |
|                      | ICTNETR07    | 0.386       |
| SCUTKapok            | SCUTKapok1   | 0.313       |
|                      | SCUTKapok2   | 0.319       |
|                      | SCUTKapok3   | 0.314       |
|                      | SCUTKapok4   | 0.318       |
|                      | SCUTKapok5   | 0.320       |
|                      | SCUTKapok6   | 0.323       |
|                      | SCUTKapok7   | 0.322       |
| U Lugano             | U LngFWBsNoOp | 0.251       |
|                      | U LngFWBsOp  | 0.224       |
| dragon               | FW14basemR   | 0.322       |
|                      | FW14basemW   | 0.260       |

7. Experimental Results

The implementation is performed on 3.06 GHz Pentium Dual Core computer with 3 GB RAM, running on Windows 7. Java scripting programming language is used; since it is a web platform and an Object Oriented Language which has security packages. The proposed approach is based on a normalization scheme which uses mean value of our previous approaches. We have implemented the proposed approach on the “http://site.uottawa.ca/~falak081” website at University of Ottawa. Figure 7 shows our output interface for a query ‘madam walker’ (some results are beyond the scope of this research paper).

8. Conclusions

Distributed indexing is crucial to find relevant information on the network. Various indexing methods are used in a wide range of applications. In this research paper, we described the idea behind our indexing approach for extending the agent information retrieval system using multi-search criteria. We proposed a natural language processing approach for the keyword search in order to allow better matching with the textual descriptions. We implemented a combination scheme for matching multiple criteria that are formally structured in many attributes in the repository. The proposed approach is robust for determining the appropriate attributes. The proposed index is structured as a memory-based hash file that able to index the information of fifty resources distributed topically in several agents that totally satisfy most information retrieval and web search topics. Currently, hash files can be used only for indexing limited size of data. Hash index schema is robust if used in real-time environment since it comprises very fast search and query response time applicable. We believe that the traditional approaches based on the data crawled index are not applicable so far since data becomes diverse and grows impressively; especially when it is incorporated.
with social media.

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APPENDIX (A): TEST QUERIES

| ID   | Query                                      |
|------|--------------------------------------------|
| 7001 | LHC collision publications                 |
| 7003 | Male circumcision                          |
| 7004 | z-machine                                  |
| 7007 | Allen Ginsberg Howl review                 |
| 7009 | linkedin engineering                       |
| 7018 | audiobook Raymond e feist                  |
| 7025 | M/G/1 queue                                |
| 7030 | Lyrics Bangarang                           |
| 7033 | Porto                                      |
| 7034 | sony vaio laptop                           |
| 7039 | import .csv excel                          |
| 7040 | vom fass gent                              |
| 7042 | bmw c1                                     |
| 7046 | tuning fork                                |
| 7047 | Dewar ask                                  |
| 7056 | ROADM                                      |
| 7067 | used kindle                                |
| 7068 | Speech and Language Processing:            |

APPENDIX (B): TRAINING RESOURCES

| ID   | Name          | Categories  | ID   | Name          | Categories  |
|------|---------------|-------------|------|---------------|-------------|
| e001 | arXiv.org     | Academic    | e099 | Bing News     | News        |
| e002 | CCSB          | Academic    | e100 | Chronicling America | News |
| e003 | CERN Documents| Academic    | e101 | CNN           | News        |
| e004 | CiteSeerX     | Academic    | e102 | Forbes        | News        |
| e005 | CiteULike     | Academic    | e103 | Google News   | News        |
| e006 | Economists Online | Academic  | e104 | JSOnline     | News        |
| e007 | eScholarship  | Academic    | e106 | Slate         | News        |
| e008 | KFUPM ePrints | Academic    | e107 | The Guardian  | News        |
| e009 | MPRA          | Academic    | e108 | The Street    | News        |
| e010 | MS Academic   | Academic    | e109 | Washington post | News       |
| ID   | Name              | Categories      | ID   | Name       | Categories      |
|------|-------------------|-----------------|------|------------|-----------------|
| e011 | Nature            | Academic        | e110 | HNSearch   | News,Tech       |
| e012 | Organic Eprints   | Academic        | e111 | Slashdot   | News,Tech       |
| e013 | SpringerLink      | Academic        | e112 | The Register | News,Tech     |
| e014 | U. Twente         | Academic        | e113 | DeviantArt | Photo/Pictures  |
| e015 | UAB Digital       | Academic        | e114 | Flickr     | Photo/Pictures  |
| e016 | UQ eSpace         | Academic        | e115 | Fotolia    | Photo/Pictures  |
| e017 | PubMed             | Academic,Health | e117 | Getty Images | Photo/Pictures |
| e018 | LastFM             | Audio           | e118 | IconFinder | Photo/Pictures  |
| e019 | LRYICSnMUSIC       | Audio           | e119 | NYPL Gallery | Photo/Pictures |
| e020 | Comedy Central     | Audio,Video     | e120 | OpenClipArt | Photo/Pictures  |
| e021 | Dailymotion       | Audio,Video     | e121 | Photobucket | Photo/Pictures  |
| e022 | YouTube            | Audio,Video     | e122 | Picasa     | Photo/Pictures  |
| e023 | Google Blogs       | Blogs           | e123 | Picsearch  | Photo/Pictures  |
| e024 | LinkedIn Blog      | Blogs           | e124 | Wikimedia   | Photo/Pictures  |
| e025 | Tumblr             | Blogs           | e126 | Funny or Die | Video,Photo/Pictures |
| e026 | WordPress          | Blogs           | e127 | 4Shared    | Audio,Video,Books,Photo/Pictures |
| e027 | Columbus Library   | Books           | e128 | AllExperts | Q&A             |
| e028 | Goodreads          | Books           | e129 | Answers.com | Q&A             |
| e029 | Google Books       | Books           | e130 | Chacha     | Q&A             |
| e030 | NCSU Library       | Books           | e131 | StackOver ow | Q&A             |
| e032 | IMDb               | Encyclopedia    | e132 | Yahoo Answers | Q&A             |
| e033 | Wikibooks          | Encyclopedia    | e133 | MetaOptimize | Academic,Q&A   |
| e034 | Wikipedia          | Encyclopedia    | e134 | HowStu Works | Kids,Q&A       |
| e036 | Wikispecies        | Encyclopedia    | e135 | AllRecipes | Recipes        |
| e037 | Wiktionary         | Encyclopedia    | e136 | Cooking.com | Recipes        |
| e038 | E? Online          | Entertainment   | e137 | Food Network | Recipes        |
| e039 | Entertainment Weekly | Entertainment   | e138 | Food.com   | Recipes        |
| e041 | TMZ                | Entertainment   | e139 | Meals.com  | Recipes        |
| e042 | The Sun            | Entertainment,Sports,News | e140 | Amazon   | Shopping       |
| e043 | Addicting games   | Games           | e141 | ASOS      | Shopping       |
| e044 | Amorgames          | Games           | e142 | Craigslist | Shopping       |
| e045 | Crazy monkey games | Games         | e143 | eBay      | Shopping       |
| e047 | GameNode           | Games           | e144 | Overstock  | Shopping       |
| e048 | Games.com          | Games           | e145 | Powell’s   | Shopping       |
| e049 | Miniclip           | Games           | e146 | Pronto     | Shopping       |
| e050 | About.com          | General         | e147 | Target     | Shopping       |
| e052 | Ask                | General         | e148 | Yahoo? Shopping | Shopping       |
| e055 | CMU ClueWeb        | General         | e152 | Myspace    | Social         |
| e057 | Gigablast          | General         | e153 | Reddit     | Social         |
| e062 | Baidu              | General         | e154 | Tweepz     | Social         |
| e063 | CDC                | Health          | e156 | Cnet       | Software       |
| e064 | Family Practice notebook | Health         | e157 | GitHub     | Software       |
| e065 | Health Finder      | Health          | e158 | SourceForge | Software       |
| e066 | HealthCentral      | Health          | e159 | bleacher report | Sports        |
| e067 | HealthLine         | Health          | e160 | ESPN       | Sports         |

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| ID    | Name                  | Categories | ID    | Name               | Categories |
|-------|-----------------------|------------|-------|--------------------|------------|
| e068  | Healthlinks.net       | Health     | e161  | Fox Sports         | Sports     |
| e070  | Mayo Clinic           | Health     | e162  | NBA                | Sports     |
| e071  | MedicineNet           | Health     | e163  | NHL                | Sports     |
| e072  | MedlinePlus           | Health     | e164  | SB nation          | Sports     |
| e075  | U. of Iowa hospitals and clinics | Health | e165  | Sporting news     | Sports     |
| e076  | WebMD                 | Health     | e166  | WWE                | Sports     |
| e077  | Glassdoor             | Jobs       | e167  | Ars Technica       | Tech       |
| e078  | Jobsite               | Jobs       | e168  | CNET               | Tech       |
| e079  | LinkedIn Jobs         | Jobs       | e169  | Technet            | Tech       |
| e080  | Simply Hired          | Jobs       | e170  | Technorati         | Tech       |
| e081  | USAJobs               | Jobs       | e171  | TechRepublic       | Tech       |
| e082  | Comedy Central Jokes.com | Jokes | e172  | TripAdvisor       | Travel     |
| e083  | Kickass jokes         | Jokes      | e173  | Wiki Travel        | Travel     |
| e085  | Cartoon Network       | Kids       | e174  | 5min.com           | Video      |
| e086  | Disney Family         | Kids       | e175  | AOL Video          | Video      |
| e087  | Factmonster           | Kids       | e176  | Google Videos      | Video      |
| e088  | Kidrex                | Kids       | e178  | MeFeedia           | Video      |
| e089  | KidsClicks?           | Kids       | e179  | Metacafe           | Video      |
| e090  | Nick jr               | Kids       | e181  | National geographic| Video      |
| e091  | Nickelodeon           | Kids       | e182  | Veoh               | Video      |
| e092  | OER Commons           | Kids       | e184  | Vimeo              | Video      |
| e093  | Quintura Kids         | Kids       | e185  | Yahoo Screen       | Video      |
| e095  | Foursquare            | Local      | e200  | BigWeb             | General    |
| e098  | BBC                   | News       |       |                    |            |
ARTICLE

Quantum Algorithm of Imperfect KB Self-organization Pt I: Smart Control-Information-Thermodynamic Bounds

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ABSTRACT

The quantum self-organization algorithm model of wise knowledge base design for intelligent fuzzy controllers with required robust level considered. Background of the model is a new model of quantum inference based on quantum genetic algorithm. Quantum genetic algorithm applied on line for the quantum correlation’s type searching between unknown solutions in quantum superposition of imperfect knowledge bases of intelligent controllers designed on soft computing. Disturbance conditions of analytical information-thermodynamic trade-off interrelations between main control quality measures (as new design laws) discussed in Part I. The smart control design with guaranteed achievement of these trade-off interrelations is main goal for quantum self-organization algorithm of imperfect KB. Sophisticated synergetic quantum information effect in Part I (autonomous robot in unpredicted control situations) and II (swarm robots with imperfect KB exchanging between “master - slaves”) introduced: a new robust smart controller on line designed from responses on unpredicted control situations of any imperfect KB applying quantum hidden information extracted from quantum correlation. Within the toolkit of classical intelligent control, the achievement of the similar synergetic information effect is impossible. Benchmarks of intelligent cognitive robotic control applications considered.

1. Introduction

According to the definition of modern control problems, the achievement of required robustness property for a complex ill-defined control object models is possible with applying the computational intelligence toolkit. The goal of this article is the description of the applied aspects of developed intelligent design technology of robust knowledge bases (KB) [1-7] using the information synergy effects of quantum knowledge self-organization [2] in unpredicted and risk control conditions [3].

Physical extractable maximal amount work and the information source correlation between the system and the memory. The maximal amount work extractable from the system is bound by the nonequilibrium free energy change [8,9]. Entropy and correlation reversely related. Work can be extracted from the correlation between subsystems and the mutual memory of correlations [10]. Dissipative information amount characterizes a waste of such correlation work. Thus, positive quantum dissipative information characterizes a potential work waste and the information related to the environments is considered as lost. The
conditional mutual information can be regarded as a part of the entropy production. The conditional free energy is equal to the maximal extractable work from the system given the memory information amount. In other words, more work can be extracted from the correlation between the system and the memory if the correlation is accessible [11]. Considered statements are the physical source background for design of considered quantum algorithm based on work done applying extractable hidden quantum information amount from classical control states.

Information-thermodynamic background of self-organization quantum algorithm. Classical states of dynamic processes include hidden quantum information that considered as additional information source for the compensation of value work waste. It is possible produce additional control action with extractable work and hidden quantum amount information in classical states is the resource of this value work. Information is physical and applied for the implementation of self-organization processes in intelligent control system using quantum - classical correlation between classical states. Four statements from quantum information theory and quantum thermodynamics are applied in this developed approach: 1) minimum entropy production rate principle of the system “control object + intelligent controller” that quadrantes the achievement of control goal with minimum of work waste in control object and in intelligent controller; 2) minimum information entropy principle for design intelligent cognitive controller that required minimum of initial information for intelligent controller action; 3) the amount of the work wasted on the extraction of hidden quantum information is less than the amount of work done on the received extracted quantum hidden information; and 4) the solution problem search of maximum extractable value work identical to a search of the minimum wasted entropy done on this work extraction. (see in details Appendix 1 [4-12]).

The article task (as the continuation of [1-7]) is the description of the IT-design processing a robust sophisticated KB of intelligent cognitive controller that produces control force that is satisfied to these requirements.

2. Problem Statement: Main Tasks

The development and applications computational intelligence toolkit is the background of the end-to-end quantum computing technology [2,5,13]. As a consequence, one of subproblems is the creation for practical quantum algorithm realization (in on line) the process correction of time-dependent parameters of conventional PID controllers for its adaptation and robustness achievement in on line.

Remark. Many control theoretic algorithms augment the basic delta rule with additional control terms that greatly improve accuracy, stability, and responsivity. The most popular variant of these control theoretic models is the popular proportional-integral-derivative (PID) controller. This model is simple, accurate, and robust, with response properties that have been well characterized over the last century. The PID controller takes the error from a reference signal as input, and it outputs a control signal consisting of a linear combination of control signals proportional to the error (P-Term), the integral of the error (I-Term), and the derivative of the error (D-Term). These three terms minimize deviations from the reference based on errors in the present, past, and expected future, respectively. Proportional control (cf. delta-rule control) directly minimizes deviation from the reference and is often the primary driver of the control process. Integral control provides low-frequency compensation for residual steady-state errors, allowing the controller to reduce noise and track gradual changes in the environment. Derivative control provides high-frequency compensation that increases stability, such as by dampening control adjustments when the controller is approaching the reference or increasing adjustments when the reference or environment suddenly changes. Intuitively, integral control provides low-frequency compensation by combining several time points, whereas derivative control provides high-frequency compensation by tracking the instantaneous change. To behave adaptively in environments that are noisy and nonstationary, humans and other animals must monitor feedback from their environment and adjust their predictions and actions accordingly. An understudied approach for modeling these adaptive processes comes from the engineering field of control theory, which provides general principles for regulating dynamical systems, often without requiring a generative model. The proportional-integral-derivative (PID) controller is one of the most popular models of industrial process control. The proportional term is analogous to the “delta rule” in psychology, adjusting estimates in proportion to each error in prediction. The integral and derivative terms augment this update to simultaneously improve accuracy and stability. Here, it tested whether the PID-controller with time-dependent coefficient gain schedule can describe how people sequentially adjust their predictions of control object in response to new information.

Problem statement. Principle of the minimum of the generalized entropy of the system (“control object + conventional controller”) considered as the fitness function in quantum genetic algorithm (QGA) and considered as a computed robustness measure. QGA-model embedded in the structure of quantum search algorithm and search
quantum types of correlation between solutions in quantum superposition (of classical control states that designed with soft computing technology). The information technology (IT) of KB remote design of the fuzzy controllers developed on the base of the "Soft / Quantum computing KB optimizer" software toolkit (SCOptKB & QSCOptKB)™. Mathematical background of the toolkit is quantum soft computing [5,13]. In Parts I and II applied Benchmarks of the developed IT design in detail discussed. In particular cases, in the design stage framework of robust KBs applying the model of quantum fuzzy inference (QFI): two different models of robots - mobile manipulator and inverted swing pendulum (“cart - pole” system) are shown.

A comparison of the quality control in the fuzzy controllers and quantum fuzzy controller in various control modes presented. The ability to connect and work with a real control object, without using his mathematical model described. The implemented technology of knowledge sharing in a swarm of intelligent robots, with quantum controllers, allows to achieve the goal of control and to gain additional knowledge by creating a new information source based on the synergetic effect of combining knowledge. The results of the experiments demonstrate the possibility of the ensured achievement of the control goal of a group of robots applying end-to-end quantum computing technology design of KBs of smart controllers in control system loop. The developed software toolkit allows to design and setup complex ill-defined and weakly formalized technical systems on line.

In Part I we consider the sophisticated structure of quantum control algorithm as the background for the QFI - model design in Part II.

3. Imperfect KB Quantum Self-organization Process

The role of specific quantum hidden information effects for smart control design described in [2]. The amount of hidden quantum information [2,3,4,6] extracted from control classical states considered as the additional information-thermodynamic control force source.

3.1 Quantum Supremacy Effects of Imperfect KB Self-organization

In natural systems the sought robustness property is coded in the algorithm of reproduction of the self-organization process [1,2]. The man-made quantum self-organization control process of the robustness property achievement of the KB is demonstrated in Figure 1.

Natural evolution processes are based on the following steps: (i) templating; (iii) self-assembling; and (iii) self-organization (level 2 in Figure 1).

Remark. Analysis of self-organization models on Figure1 gives us the following results. Models of self-organization are included natural quantum effects and based on the following information-thermodynamic concepts: (i) macro- and micro-level interactions with information exchange (in agent-based models - ABM - micro-level is the communication space where the inter-agent messages are exchange and is explained by increased entropy on a micro-level); (ii) communication and information transport on micro-level (“quantum mirage” in quantum corals); (iii) different types of quantum spin correlation that design different structure in self-organization (quantum dot); (iv) coordination control (as example, swarm-bot and snake-bot).

According quantum computing theory in general form every quantum algorithm (QA) includes the following unitary quantum operators: (i) superposition; (ii) entanglement (quantum oracle); (iii) interference. Measurement is the fourth classical operator. [It is irreversible operator and is used for measurement of computation results].

Quantum control algorithm of self-organization that developed in Figure 1 (level 1) is based on quantum fuzzy inference (QFI) models. QFI includes these concepts of self-organization and has realized by corresponding quantum operators.

QFI is one of possible realization of quantum control algorithm of self-organization that includes all of these features: (i) superposition; (ii) selection of quantum correlation types; (iii) information transport and quantum oracle; and (iv) interference. With superposition is realized templating operation, and based on macro- and micro-level interactions with information exchange of active
agents. Selection of quantum correlation type organize self-assembling using power source of communication and information transport on micro-level. In this case the type of correlation defines the level of robustness in designed KB of FC. Quantum oracle calculates intelligent quantum state that includes the most important (value) information transport for coordination control. Interference is used for extraction the results of coordination control and design in on-line robust KB.

The developed QA of self-organization is applied to design of robust KB of FC in unpredicted control situations. Main operations of developed QA and concrete examples of QFI applications are described.

Fulfillment of requirements in the information - thermodynamic criteria (see Figure 1, level 3) guarantee in on line invariant control objective reaching of smart control with the required robustness level.

The corresponding design process shown in [2-4] as following:

\[
\begin{align*}
\text{Designed self-organized robust state} & = \\
\quad \text{Evolution of self-organization process} & \quad \text{Problem orientation of control object} \\
& \quad \text{Quantum random search} \quad \text{Correlation type and form} \\
& \quad \text{Initial state} \quad \text{Classical, quantum, mixed} \\
& \quad \text{"Building" block} \quad \text{Initial state} \quad \text{Reproduction} \\
& \quad \text{State of output of fuzzy controller for new control error}
\end{align*}
\]

(1)

Let us consider particular case (1).

3.2. Quantum Self-organization of Imperfect KBs

For design of production rules of KB in intelligent hybrid PID controller the structure of corresponding quantum algorithm has the following form from (1) [in Figure 1 (level 3)]:

\[
\begin{align*}
\text{Control gains schedule of hybrid PID controller} & = \\
\quad \text{Quantum algorithm of robust knowledge base self-organization} \quad \text{Output} \\
& \quad \text{Inference} \quad \text{State with the max \{probability amplitude\}} \\
& \quad \text{Quantum random search} \quad \text{Superposition} \\
& \quad \text{Problem orientation of control object} \quad \text{Quantum computational intelligence toolkit} \\
& \quad \text{Type and form of correlation} \quad \text{Choice of quantum correlation form} \\
& \quad \text{Formation of quality and depth of knowledge representation} \\
& \quad \text{"Building" block} \quad \text{Initial state} \\
& \quad \text{State of output of fuzzy controller for new control error}
\end{align*}
\]

(2)

Figure 2 demonstrates the structure of robust intelligent control system based on quantum fuzzy inference (QFI).

In Figure 2 the box SCO - soft computing optimizer toolkit (SCOOptKB™) - design KBs of fuzzy controllers (FC1 and FC2) on learning situations that can be non-robust (imperfect) in other control situations. The input of the quantum fuzzy inference (Box QFI) with QGA extract a hidden quantum information from imperfect knowledge base (KB) responses of fuzzy controllers FC1 and FC2 on unpredicted control errors realized quantum fuzzy controller in on line without changing production rules numbers of KBs in FC1 and FC2 [1].

3.2.1 QFI Structure

It is shown that in quantum computing the construction of a universal quantum simulator based on classical effective simulation is possible [1-7]. In the general form, the model of quantum algorithm computing comprises the following five stages:

• preparation of the initial state \(|\psi_{\text{in}}\rangle\) (classical or quantum);
• execution of the Hadamard transform for the initial state in order to prepare the superposition state;
• application of the entangled operator or the quantum correlation operator (quantum oracle) to the superposition state;
• application of the interference operator;
• application of the measurement operator to the result of quantum computing \(|\psi_{\text{out}}\rangle\).

Hence, a quantum gate approach can be used in a global optimization of KB structures of ICSs that are based on quantum computing, on a quantum genetic search and quantum deep learning algorithms [3,7].

3.2.2 Quantum Information Resources in QFI Algorithm

Figure 3 shows the algorithm for coding, searching and
extracting the value information from two KBs of fuzzy PID controllers designed by SCO.

Therefore, the domain of efficient functioning of the structure of the intelligent control system can be essentially extended by including robustness, which is a very important characteristic of control quality. The robustness of the control signal is the background for maintaining the reliability and accuracy of control under uncertainty conditions of information or a weakly formalized description of functioning conditions and/or control goals. QFI model based on physical laws of quantum information theory, for computing use unitary invertible (quantum) operators and they have the following names: superposition, quantum correlation (entangled operators), and interference. The fourth operator, measurement of result quantum computation is irreversible.

Optimal drawing process of value information from a few KBs that are designed by soft computing is based on following four facts from quantum information theory: (i) the effective quantum data compression; (ii) the splitting of classical and quantum parts of information in quantum state; (iii) the total correlations in quantum state are “mixture” of classical and quantum correlations; and (iv) the exiting of hidden (locking) classical correlation in quantum state [6].

This quantum control algorithm uses these four Facts from quantum information theory: (i) compression of classical information by coding in computational basis \([\{0\}, \{1\}]\) and forming the quantum correlation between different computational bases (Fact 1); (ii) separating and splitting total information and correlations on “classical” and “quantum” parts using Hadamard transform (Facts 2 and 3); (iii) extract unlocking information and residual redundant information by measuring the classical correlation in quantum state (Fact 4) using criteria of maximal corresponding amplitude probability. These facts are the informational resources of QFI background. Using these facts, it is possible to extract an additional amount of quantum value information from smart KBs produced by SCO for designing a wise control using compression and rejection procedures of the redundant information in a classical control signal.

Quantum algorithmic gate (QAG) based on QGA, as extended QFI-structure on Figure 5, is:

\[
QAG = \left[ \left( \text{Int} \otimes I \right) \cdot U_r \right]^{d+1} \cdot \left[ H \otimes \Phi \right]^{n} S
\]

Figure 5 demonstrates QAG for QFI based on QAG. The entangled state design of operator \(U_r\) in Equation (3) correspond to design of the quantum search algorithm type.
rigorous result is that interconnection of PCHS by means of
what is called a Dirichlet structure yields an implicit
PCHS. A basic property of PCHS is the energy balanc-
ing property \( \frac{dH}{dt}(x,t) \leq u'(t)y(t) \) showing that a PCHS
is passive if the Hamiltonian \( H \) is bounded from below.
Physically the internal interconnection structure is pow-
er-conserving and the term \( u'(t)y(t) \) is the externally
supplied power.

It is well-known \(^{14}\) that physically different subsys-
tems of complex control objects (with different physi-
cal nature of subsystems) presented as Port-controlled
Hamiltonian (PCH) systems can be considered as
generalization structures of conventional Hamiltonian
systems \(^{15}\). We briefly describe the main idea of PCH
systems model.

4.2 Port-controlled Hamiltonian Quantum Mod-
dels

The quantum port-Hamiltonian framework is the general-
ization of conventional model of PCH and can be illustrated
on its application using RLC circuits \(^{16}\). These RLC circuits
are then used to construct the primitive gate set for universal
quantum computation, i.e., the phase-shift, Hadamard, and
CNOT gates, and are synthesized with the composite Dirac
structures (see, the definition Dirac structure in item 4.1)
of the quantum-port-Hamiltonian framework.

Model presentation of quantum PHS. For this purpose,
firstly, a Schrödinger equation for the universal RLC quan-
tum circuit is introduced applying the definition of a quan-
tum port-Hamiltonian system. Let \( P \in \mathbb{C}^{m\times n} \) be invertible
and self-adjoint, let \( P_{\alpha} \in \mathbb{C}^{m\times n} \) be skew-adjoint, i.e., \( P_{\alpha} = -P_{\alpha}^T \), and let \( \mathcal{H} \in \mathbb{C}^{n\times n} \), \( \{ \mathcal{H}_j \}_{j=0}^{N} \), where \( j \in \mathbb{N} \) such that
\( \mathcal{H}_j = \mathcal{H}_j^* \), \( m \leq \mathcal{H}_j \leq M \) for a.e. \( j \in [0,N] \) and constants \( M \); \( M \geq 0 \) independent of \( j \). The Hilbert space \( X = \mathbb{C}^{\{ j=0,...,N \}, \mathbb{C}^n} \)
with the discrete inner product (see the standard definition of
quantum mechanics, for example \(^{17}\))

\[
\langle \psi, \phi \rangle = \frac{1}{4} \sum_{j=0}^{N} \langle \phi, \psi_j \rangle \langle \psi_j, \psi \rangle + \frac{1}{2} \sum_{j=0}^{N} \langle \phi_j, \psi \rangle \langle \psi, \phi_j \rangle + \frac{1}{4} \sum_{j=0}^{N} \langle \phi_j, \psi_j, \psi \rangle 
\]

Then the linear first-order Schrödinger equation \( i\hbar \frac{d}{dt} \psi \)
\( \psi(t) = \frac{1}{2} \sum_{j=0}^{N} \langle \psi_{j+1}, \psi_j \rangle \psi_j(t) + \frac{1}{2} \sum_{j=0}^{N} \langle \psi_{j-1}, \psi_j \rangle \psi_j(t) + 

P \sum_{j=0}^{N} \mathcal{H}_j \psi_j(t) \) is a quantum PHS \( \mathcal{H} \), where \( \hbar \) is the redu-
ced Planck constant, the imaginary number \( i = \sqrt{-1} \), and
the instantaneous state of the quantum system is \( \psi(t) = 
\sum |a_j(t)|^2 \), where the complex number \( a_j(t) \) is \( a_j(t) =
\langle j | \psi(t) \rangle \) and \( \langle j | \rangle = \delta_{j} \).
Example. Let us consider a state space manifold $\chi$ and a Hamiltonian $H$: $\chi \to \mathbb{C}$, defining energy-storing state, e.g. current $I$ or voltage $V$. A quantum port-Hamiltonian system on $\chi$ is defined by the Dirac structure $\mathcal{D}=T_{\chi} \otimes T_{\chi} \otimes \mathcal{P} \otimes \mathcal{L}$ having energy-storing port $(f_{\text{e}}, e_{\text{e}}) \in T_{\chi} \otimes T_{\chi} \otimes \mathcal{P} \otimes \mathcal{L}$ and an external structure $\mathcal{P}$, e.g. source voltage or output current, such that $\mathcal{P} \subset \mathcal{E} \otimes \mathcal{L}$, corresponding to an external port $(f_{\text{p}}, e_{\text{p}}) \in \mathcal{P} \otimes \mathcal{L}$. The temporal dynamics of the quantum system are then specified by

$$\dot{a}(t)=\frac{\partial}{\partial t}(H) \cdot \pi + \frac{\partial}{\partial t}(H), f_{\text{p}}(t), e_{\text{p}}(t) \in \mathcal{D}(a(t)), \quad t \in \mathbb{R},$$

where $a_{\pi}$ are the coordinated generalizations, and $\pi_{\pi}$ are the conjugate momenta.

For purposes of quantum state preparation with universal RLC circuit design adapting some classical theory of the Operational Transconductance Amplifier (OTA) as seen in Figure 6.

**Figure 6.** (a) RLC circuit equivalent of the quantum channel.

(b) Quantum Port-Hamiltonian System representation of the RLC quantum channel (a)

Let us describe the details on Figure 6. On Figure 6a Digital-to-Analog Conversion (DAC) is used to prepare the analog quantum state, which then propagates along the $z$-direction. The time-dependent Dirac structure $\mathcal{D}(t)$ then performs a unitary evolution of the prepared quantum state. The current across the resistor(s) is $I_{\text{r}}(t) = g_{\text{in}}V_{\text{in}}(t) - V_{\text{out}}(t)$, where $g_{\text{in}}$ and $V_{\text{out}}(t)$ are the current storage state, and efforts $(f_{\text{e}}, e_{\text{e}})$ respectively across the capacitor(s). The electric power-balance (conservation) equation is $H = i \hbar \mathcal{O}_{\text{h}}$, such that the total power is equal to zero (color online).

The output current of an OTA is proportional to the input signal voltage, such that $I_{\text{out}} = g_{\text{in}}(V_{\text{in}}(t) - V_{\text{out}}(t))$ and the $j$-th RLC circuit site current with continuous (time-dependent) phases [10] is described as

$$I_{\text{out}}(t) = \frac{g_{\text{in}}}{\exp[i\omega t - \varphi]} \left[ |\psi_{\text{in}}| \exp[i\omega t] - |\psi_{\text{out}}| \exp[i\omega t] \right].$$

For clarification purposes cf. qubits, here it should be pointed out that the quantum superposition state(s) prepared by the OTA(s) is $|\psi(t)\rangle = |\psi_{\text{out}}(t)\rangle$, such that $|\psi(t)\rangle = \sqrt{i} \exp[i\omega t - \varphi]$, $|\psi(t)\rangle = \sqrt{i} \exp[i\omega t - \varphi]$

and the superposition state $|\psi(t)\rangle = |\psi_{\text{in}}(t)\rangle \pm |\psi_{\text{out}}(t)\rangle$.

The solution of Equation (6) is a bright soliton propagation along the RLC quantum channel

$$I_{\text{r}}(t) = \frac{1}{2\omega_{\text{r}}^2} \left[ |V_{\text{in}}(t) - V_{\text{out}}(t)|^2 \right],$$

$$V_{\text{r}}(t) = \frac{1}{2c_{\text{r}}} \left[ I_{\text{in}}(t) - I_{\text{out}}(t) + 2 \left| \sin \left( \frac{2\pi}{\phi_{\text{r}}} \phi_{\text{r}}(t) \right) \right| \right], \quad \phi_{\text{r}}(t) = V_{\text{r}}(t).$$

The solution of Equation (6) is a bright soliton propagation along the RLC quantum channel as seen in Figure 6a. As such, the analytical solution is [16]

$$\phi_{\text{r}}(t) = \frac{2\pi}{\phi_{\text{r}}} \sin \left( \frac{\text{e}^{-\frac{\lambda}{\sqrt{2}}} - \text{e}^{\frac{\lambda}{\sqrt{2}}}}{c} \right), \quad V_{\text{r}}(t) = \frac{2\pi}{\phi_{\text{r}}} \phi_{\text{r}}(t) = \frac{2\pi}{\phi_{\text{r}}} \text{sech} \left( \frac{\text{e}^{-\frac{\lambda}{\sqrt{2}}} - \text{e}^{\frac{\lambda}{\sqrt{2}}}}{c} \right)$$

The statement of the Heisenberg uncertainty principle is the following: $\langle \hat{x}^2 \rangle \langle \hat{p}^2 \rangle \geq \frac{1}{2} \hbar^2$.

Furthermore, here it should be pointed out that the position observable $x = j \Delta z = j$ and the momentum ob-
servable \( \hat{p} = -i\hbar \frac{\partial}{\partial z} \), thereby satisfying the Heisenberg uncertainty principle \( \langle \hat{p}^2 \rangle \langle \hat{z}^2 \rangle \geq \frac{1}{4} \hbar^2 \).

4.3 Information-thermodynamic Laws of Intelligent Cognitive Control

Let us describe control object model as (4) in the generalized form

\[
\frac{dq}{dt} = \varphi(q, S(t), t, u, \xi(t)), \quad u = f(q, q_i, t),
\]

where \( q \) is the vector of generalized coordinates describing the dynamics of the controlled plant; \( S \) is the generalized entropy of dynamic system (4); \( u \) is the control force; \( q_i(t) \) is reference signal, \( \xi(t) \) is random disturbance.

**Remark:** Definitions of Stability Conditions and Instability Theorems. To describe a nonlinear system's behavior, two theorems help to characterize the essential features of its motion. In addition, by bounding the Lyapunov function between these Theorems, both necessary and sufficient conditions are a result of the transition of the time derivative of the Lyapunov function from stable to unstable \(^{[13]}\).

1) Lyapunov Theorem for Stability. Assume that there exists a scalar function \( V \) of the state \( x \), with continuous first order derivatives such that

- \( V(x) \) is positive definite; \( V(x) \rightarrow \infty \) as \( |x| \rightarrow \infty \).

Then the equilibrium at the origin is globally asymptotically stable.

2) Chetaev Theorem for Instability. Considering the equations of disturbed motion, let \( V \) be zero on the boundary of a region \( R \) which has the origin as a boundary point, and let both \( V \) and \( V \) be positive-definite in \( R \); then the undisturbed motion is unstable at the origin.

The necessary and sufficient conditions of asymptotic stability of dynamic system (7) with \( \xi(t) = 0 \) are determined by the physical constraints (for example, as for PCHS) on the form of the Lyapunov \( V \) function:

- \( V > 0 \); \( \frac{dV}{dt} \leq 0 \).

The generalized Lyapunov function has the form \(^{[6]}\):

\[
V = \frac{1}{2} \sum q_i^2 + \frac{1}{2} S^2,
\]

where \( S = S_r - S_s \) is the production of entropy in the open system “control object + controller”, \( S_r = \Psi(q, q_i, t) \) is the production of entropy in the controlled plant; and \( S_s = \Phi(\xi, t) \) is the production of entropy in the controller (actuator of the automatic control system).

Thus, taking into account (7), received final expression as following:

\[
\frac{dV}{dt} = \sum q_i \varphi(q, (\Psi - \bar{Y}), t, u) + (\Psi - \bar{Y})(\Psi - \bar{Y}) \leq 0
\]

**Remark.** Let us briefly consider Equation (8). Derivative of the function \( V \) can be described as \( \frac{dV}{dt} = \sum q_i \varphi + SS = \sum q_i \varphi_s (q, S(i), t, u, \xi(i)) + (\Psi - \bar{Y})(\Psi - \bar{Y}) \) and we have Equation (9). The function \( V \) should be satisfied to conditions (1) and (II).

Relation (9) displayed stability, controllability, and robustness trade-off properties.

**Remark.** Equation (9) is an analytic form of the interrelations between control qualities with entropy definitions as the measure of loss controllability and robustness. This condition describes the possibility for optimum searching distribution of control level qualities for guaranteed control goal achievement in unpredicted control situations with minimal loss of working resource applying as fitness function of genetic algorithms generalized entropy from r.h.s. in (9).

**Example: Information interrelations of control qualities.** For (9) apply the well-known interrelation between Gibbs thermodynamic and Shannon information entropies. The Shannon entropy \( H(X; s) \) agrees with the usual thermodynamical entropy \( S = -1/\beta \sum \log Z(\beta) \) for a physical system with Hamiltonian \( H \) and partial function \( Z(\beta) \) at inverse temperature \( \beta = 1/T > 0 \), and free energy \( F = -\log Z(\beta) \). For the density probability function \( p(n) \) of \( Z(\beta) \) and \( Z(\beta) = \exp(-\beta \mathcal{H}) \), Spec(\( H \)) = \( \lambda_\beta \), the expression of Shannon information entropy \(^{[17,18]}\) is as following:

\[
H = -\sum n \log p(n) \log P(n) = \sum n \log Z(\beta) - \beta \sum n \lambda_n\
\]

\[
= \left[\sum \log Z(\beta) - \sum \lambda_n \lambda_n \exp(-\beta \mathcal{H}) \log Z(\beta)\right],
\]

where \( \sum \log Z(\beta) = \log Z(\beta) \).

Thus, both quantitative measures of the entropy

\[
S = \left[1 - \beta \frac{\partial}{\partial \beta}\log Z(\beta)\right] = -\sum P(n) \log P(n) = H \text{ are equivalent} \(^{[18]}\).

Therefore, the entropies \( S \) and \( H \) connected as following:

\[
S = kH = -k \sum p_i \log p_i, \quad k \approx 1.38 \times 10^{-23} \frac{\text{erg}}{\text{K}}
\]

Boltzmann constant. We can introduce in (6) this relation for \( S(t) \) as Shannon information entropy \( H \). As result have following interrelation:
The demon (see a definition of Demon in [9]) may choose the current $i$ freely and has access to the noisy voltage measurement $\delta_{\text{meas}}$. Consider the overdamped Langevin equation [23]

$$\tau \dot{\vartheta} = -\vartheta + Ri + \sqrt{2kTRw}, \quad \tau = RC, \quad \langle \vartheta(0) \rangle = 0; \quad \vartheta_{\text{meas}} = \vartheta + \sqrt{V_{\text{meas}}W_{\text{meas}}}.$$ 

with $\vartheta(0)$ Gaussian, $w$ and $w_{\text{meas}}$ uncorrelated Gaussian white noise $\langle \{w(t)w(t')\} \rangle = \langle w_{\text{meas}}(t)w_{\text{meas}}(t') \rangle = \delta(t-t')$; $V_{\text{meas}}$ the intensity of the measurement noise. The work-extraction rate of the demon is $W$, can define that, $U = \dot{\vartheta} - \dot{W}$, where $U = \frac{1}{2}C\dot{\vartheta}^2 = \frac{1}{2}kT_C$, $\dot{\vartheta} = \frac{k}{\tau}(T - T_C)$. $\dot{W} = -\langle \dot{\vartheta} \rangle$. (16)

The voltage $\vartheta_{\text{meas}}$ is the measurement that supplies the demon with information. The Kalman-Bucy filter state is defined $\dot{\vartheta}$ and we have: $\tau \frac{d}{dt} \dot{\vartheta} = -\dot{\vartheta} + Ri + K(\vartheta_{\text{meas}} - \dot{\vartheta})$, $\dot{\vartheta}(0) = 0$, where $K$ is an optimal gain ($K_\text{opt}$), the Kalman gain, that will minimize the estimation error variance $\min_{K} \langle (\vartheta(t) - \dot{\vartheta}(t))^2 \rangle$ (a filter Riccati equation, for example [23]) is

$$\tau \dot{T}_{\text{min}} = 2(T - T_{\text{min}}) - \frac{\sigma T_{\text{min}}^2}{2\tau}, \quad T_{\text{min}}(0) = T,$$

where $K = \frac{\sigma T_{\text{min}}}{2\tau}$, and maximum work amount (15) quantified through the definition of the transfer entropy [23]:

$$I_C(t) = I(\langle \vartheta(0), \{w\} \rangle; \langle \vartheta_{\text{meas}} \rangle)$$

or

$$I_C(t) = \frac{1}{2V_{\text{meas}}} \int_0^t \langle (\vartheta(t) - \dot{\vartheta}(t))^2 \rangle dt = \frac{1}{2V_{\text{meas}}} \int_0^t \frac{kT_{\text{meas}}}{C} dt' = \frac{\sigma}{4\tau} \left( T - T_{\text{min}} \right) dt'.$$

Equation (11) shows that the level of robustness possible to increase apply entropy rate production of technical controller that decrease the loss of value resource of control object. Equation (12) shows that the negentropy of cognitive controller decrease the requirements to necessary initial information amount for the achievement designed level of robustness. Thus, the extracted information from knowledge base of cognitive controller gives the possibility to receive the additional resource for value work that equivalence to purposeful action on control object for quarantined achievement of control goal. That means the information is physical and the control action based on this information can produce the value work.

Figure 8 shows (see Equation (11), (12) and (14)) the information-physical law for design of smart control.
Figure 8. Information-thermodynamic trade-off between control qualities

Let us consider these statements applying analysis of the interrelation between information amount, extracted value work and free energy, and for (5) the following relation is defined:

$$\frac{d}{dt} = \begin{cases} \Delta S + k_B \ln 2 \Delta H \geq 0 & \text{Stability} \\ \frac{\Delta H}{\Delta S} & \text{Control} \\ \frac{\Delta H}{\Delta H} & \text{Robustness} \end{cases}$$

(18)

The state corresponds to the minimum system entropy and called as "equipartition of energy" [24].

Remark. According to (15) it is possible define

$$\sum_i q_i \varphi_i (\Psi - \Upsilon, t) \leq 0$$

(19)

And from (19):

1. $$\sum_i q_i \varphi_i < 0, (\Psi > \Upsilon), (\Upsilon > \Psi), S_S > 0$$
2. $$\sum_i q_i \varphi_i < 0, (\Psi > \Upsilon), (\Upsilon > \Psi), S_S > 0$$
3. $$\sum_i q_i \varphi_i < 0, (\Psi > \Upsilon), (\Upsilon > \Psi), S_S < 0, \sum_i q_i \varphi_i < S_S$$

etc. and its combinations, that means thermodynamically stabilizing compensator can constructed.

4.4 Micro-nano-robotics Intelligent Control

In this item the control modeling methodology of mobile micro robot in a blood flow fluid [25] briefly described.

Entropy Production and Dynamic Stability of a Micro-Robot in a Fluid.

The micro-robot as a mechanical system in a fluid [25] considered as:

$$m_i \ddot{x}_i + C_i \dot{x}_i + K_i \sum_1^3 (x_i - x_n) - l_i \vartheta_i = \tau(t) \quad + \xi(t) , 
 m_2 \ddot{x}_2 + C_d \dot{x}_2 + K_2 \sum_1^3 (x_2 - x_n) - l_3 \vartheta_2 - l_3 \vartheta_3 = m_3 \dot{x}_3 + C_d \dot{x}_3 + K_3 \sum_1^3 (x_3 - x_n) + \xi(t) \quad + \xi(t) , 
 l_1 l_2 l_3 \vartheta_1 l_3 \vartheta_2 l_3 \vartheta_3 = 0$$

(20)

where $$\vartheta_{n+1} = \frac{1}{3} \vartheta_{n+1} + \frac{1}{3} \vartheta_{n+1} (x_{n+1} - x_n)$$ and $$m_1 = 1.6 \times 10^{-7} \text{ kg}; m_2 = 1.4 \times 10^{-6} \text{ kg}; m_3 = 2.4 \times 10^{-6} \text{ kg}; l_1 = 2.0 \times 10^{-3} \text{ m}; l_2 = 4.0 \times 10^{-3} \text{ m}; l_3 = 4.0 \times 10^{-3} \text{ m}; K_1 = 61.1 \text{ N/m}; K_2 = 13.7 \text{ N/m}; K_3 = 23.5 \text{ N/m}; A_1 = 4.0 \times 10^{-5} \text{ m}^2, A_2 = 2.4 \times 10^{-5} \text{ m}^2, A_3 = 4.0 \times 10^{-5} \text{ m}^2;$$

$$\xi(t)$$ - stochastic excitation (white noise).

An entropy production of MMR is defined based on Equation (20) as

$$\frac{dS}{dt} = \sum_{i=1}^3 C_d \rho | \dot{x}| | \dot{x}| = \frac{1}{2}$$

(21)

and the Lyapunov function defined [26]

$$V = \sum_{i=1}^3 m_i \ddot{x}_i^2 + \sum_{i=1}^3 K_i (x_i - x_n) - l_i \vartheta_i) \leq S^2$$

(22)

where $$S = S_i - S_c$$ and $$S_c$$ is the entropy of controller with torque $$\tau$$ in Equation (20).

For the traditional form representation of (20) as

$$\dot{x}_i = \varphi(x_i, \tau, t)$$

(23)

From Equation (23) sufficient conditions can be described as following:

$$\sum_i \varphi_i (x_i, \tau, t) x_i < (S_i - S_c) \frac{dS_c}{dt} - \frac{dS_i}{dt} < 0$$

(24)

Thus, the requirements of stability design achieved with “negentropy” amount of intelligent controller. Figure 9 shows simulation results.
Figure 10 shows the result of the intelligent behavior MNR simulation based on genetic algorithm with the fitness function as the minimum entropy production (in MNR and in conventional controller.)

Figures 9 and 10 show that the intelligent behavior of the MMR can be achieved based on computational intelligence toolkit as quantum soft computing.

**Example.** A cooperative system with entropy production and rate exchange\cite{28-31} can be as:

- MMR motion (on classical level):

\[ \dot{\xi} + F(\xi, \dot{\xi}, t, S) + \frac{dV_\xi(\xi)}{d\xi} = u(t) \]  

- MMR coupled motion (non-linear Schrödinger\cite{590}):

\[ \frac{i\hbar}{\partial t} \frac{\partial^2 \Psi}{\partial \xi^2} = -\frac{\hbar^2}{2m} \frac{\partial^2 \Psi}{\partial \xi^2} + V_\xi(\xi) + F(\xi, \dot{\xi}, t, S) [x - \xi(t)] + \] 

\[ + \frac{\hbar^2}{i} (\ln \Psi - (\frac{i}{\hbar}\ln \Psi)) \Psi - 2\hbar \frac{\partial \alpha(x,t)}{\partial \xi} \Psi = H_0 \Psi \]  

- Fluid medium\cite{31}:

\[ \frac{\partial \alpha}{\partial t} = (E + \Delta E)\alpha - R_0 J(\omega) \frac{\partial^2 \alpha}{\partial \xi^2} - G |\alpha|^2 \alpha - \frac{\hbar}{2} \frac{Z_\alpha + F_r}{M} \frac{\partial}{\partial \xi} |\Psi|^2 \]  

\[ \frac{\hbar}{2} \left[ \frac{\partial}{\partial \xi} - \frac{2\hbar \alpha}{M} \frac{\partial}{\partial \xi} |\Psi|^2 \right] \]  

- Entropy exchange (between a quantum fluid medium and MMR):

\[ S = S_\rho - S_e, \]  

\[ \frac{dS_{\rho}}{dt} = 1 \frac{F(\xi, \dot{\xi}, t, S_\rho)}{T} \xi, \]  

\[ \frac{dS_e}{dt} = \Theta(\xi, \dot{\xi}, t, S_\rho, S_\rho) = \frac{S_\rho^2}{2} \ln |\Psi|^2 = -T(\rho \ln \rho), \]  

where \( S_\rho \) - the entropy production of the MMR motion; \( S_e \) - the entropy exchange between the MMR and fluid medium; \( S_\rho \) - the entropy of fluid medium (von Neumann entropy); \( T \) - the temperature (constant); \( m, \gamma \) - real constants.

For an initial coherent state of MMR the classical equation of motion is:

\[ \Psi(x,t) = \langle x | \Psi(0) \rangle = \frac{1}{\sqrt{2\pi \sigma^2}} \exp\left\{ i(k_0 x - \frac{x^2}{4d}) \right\} \]  

From Equation (31) local soliton as the solution

\[ \alpha(x,t) = \frac{\mu_0 \exp(-Zt)}{\cosh\left(\frac{\mu}{R_0} \exp(-Zt) (x - x_0 - vt)\right)} \]  

where \( \mu(x,t) = \mu_0 \exp(-Zt) \), \( N = \int \alpha(x,t) dx \), \( N \) - the occupation number of interacting quantum modes, \( k \) - wave number. The solution has the following form:

\[ \Psi = N \exp(R + iM), \quad \widetilde{x} = x - \xi(t). \]  

If we introduce the ansatz\cite{25}

\[ M(t,x,\xi) = K_x(t) + L_x(t) \widetilde{x} + M_x \xi^2 = M(\widetilde{x},t), \]  

\[ R(t,x,\xi) = -(P(x - \xi(t))^2 = -P\xi^2 = R(\widetilde{x},t), \]  

where \( K_x = \frac{1}{2} \left[ \Phi(\xi, \dot{\xi}, t) d\tau - \frac{1}{2} \frac{\omega_0^2}{\Omega} t, \Phi(\xi, \dot{\xi}, t) = \right. \]

\[ \frac{1}{2} \left[ \frac{m\xi^2}{2} - \frac{1}{2} \frac{m\omega_0^2}{\Omega} \xi^2(t); \xi + \gamma \xi + F(\xi, \dot{\xi}, t) + \omega_0^2 \xi = 0, \right. \]

\[ \frac{L_x(t) = \frac{m}{h} \xi^2, M_x(t) = -\frac{m}{h} \xi^2, P = \frac{m}{2h}, \Omega = (\omega_0 - \frac{2\hbar^2}{4})^{1/2}, \]  

then the soliton-like solution\cite{31,32}

\[ \Psi(x,t,\xi(t)) = \left( \frac{m\Omega}{\hbar} \right)^{1/4} \left( \exp\left( \frac{i}{\hbar} \left[ m\xi^2(x - \xi) - \frac{1}{4} m\rho^2(x - \xi)^2 \right] \right) \right) \]  

\[ \frac{m}{2}\Omega(x - \xi)^2 \exp\left( \frac{i}{\hbar} \left[ M_\rho(\xi, \dot{\xi}, t) \xi - \frac{1}{2} \hbar \omega_0 (\omega_0^2 t) \right] \right) \phi_\rho(x - \xi(t)) \]  

where \( \phi_\rho \) satisfies

\[ -\frac{\hbar^2}{2m} \xi^2 \phi_\rho + \frac{1}{2} m\Omega^2 \xi^2 \phi_\rho = \epsilon_n \phi_\rho, \quad \epsilon_n = \left[ n + \frac{1}{2} \right] h\Omega, \quad n = 1,2,\ldots, y = x - \xi(t). \]  

In (25) the trajectory \( \xi(t) \) is classical and a spatio-temporal fluid motion shown in Figure 11, a.
Figure 11. a) Spatio-temporal motion of fluid medium; b) Soliton like spatio-temporal motion of MNR in dissipative nonlinear medium; c) Motion wave packet in presence of dissipation; d) Projection of motion on plain \(x^2\).

In this case the MMR-body in the initial state located and can be coupled with the soliton inner structure (41) (see Figure 11, b,c,d) and Schrödinger-like description model equation is

\[
i h \frac{\partial}{\partial t} \Psi(x,t) = -\frac{\hbar^2}{2m} \frac{\partial^2}{\partial x^2} \Psi(x,t) ,
\]

and for the final state (36) \(^{[30]}\)

\[
|\Psi(x,t)|^2 = \frac{1}{\sqrt{2\pi}} \exp \left[ - \frac{(x-k_0 t)^2}{2\sigma^2} \right]
\]

Here \(t_Z = m(1-\exp(-Z/m)) \) and \( d = \sqrt{\langle \Psi(0)|x^2|\Psi(0)\rangle - \langle \Psi(0)|x|\Psi(0)\rangle^2} \).

Thus, the control vibration of MMR creates a “fur-coat” in the form of the soliton.

Remark: Stability Lemma for Nonlinear Systems. Based on the relationship between thermodynamic exergy and Hamiltonian systems in \(^{[40]}\) a fundamental stability Lemma for Hamiltonian systems formulated. The stability of Hamiltonian systems is bounded between Lyapunov and Chetaev theorems as following: Given the Lyapunov derivative as a decomposition and sum of exergy generation rate \(W\) and exergy dissipation rate \(\alpha\) then

\[
W = \sum_{k=1}^{N} F(\xi_k,\xi_k,t,S) + \frac{dV}{dt} + (S_{pr} - S_{ex}) \left( \frac{dS_{pr}}{dt} - \frac{dS_{ex}}{dt} \right)
\]

Thus, an unstable dynamic system can be transferred into stable state applying only entropy production (intelligent control level) as a non-mechanical thermodynamic force.

\[
\dot{V} = W - T_0 S_l = \sum_{j=1}^{N} Q_j \dot{q}_j - \sum_{i=1}^{M} Q_i \dot{q}_i .
\]

where \(Q_j\) is the generalized force vector and the irreversible entropy production rate can be expressed as

\[
\dot{S}_l = \sum_{i} \dot{X}_i = \frac{1}{T_0} \sum_{i} Q_i \dot{q}_i \geq 0 .
\]

A control law is Lyapunov Optimal if it minimizes the first time derivative of the Lyapunov function over a space of admissible controls. In general, a set of feedback gains are optimized by minimizing the regulating and/or tracking error of the feedback controller while regulating to zero and/or tracking a desired reference input. The Lyapunov function is the total error energy which for most mechanical systems is equivalent to an appropriate Hamiltonian function \(H\) as \(V = H\). Then the concept of Lyapunov Optimal \(^{[40]}\) follows directly from setting \(W = 0\) in (49) and maximizing \(T_0 S_l\) for which the time derivative of the Lyapunov function (Hamiltonian) or the modified power (work/energy) equa-
tion is written as \( \dot{V} = \dot{H} = -T_w \dot{S}_j = - \sum_{j=1}^{N} Q_j \dot{q}_j = - \sum_{j=1}^{N} F_j \dot{R}_j \)
which is independent of system dynamics and is a kinematic quantity that applies to any system. Note that \( F_j \) denotes a set of forces acting on a mechanical system and \( \dot{R}_j \) denotes the inertial linear velocity of the point where \( F_j \) is applied. Passivity control for robotic systems follows directly from setting \( \dot{W} = 0 \) in (49).

Remark: Information-like Lyapunov functions. Recently, in [56] presented a rich information-like family of universal Lyapunov functions for any linear or non-linear reaction network with detailed or complex balance. Moreover, \( H_j \) are not just Lyapunov functions but divergences: \( H_j (c_i (t) c_j^*(t)) \) is monotonically non-increasing function of time \( t \) for any two kinetic curves \( c_i (t) \) and \( c_j^*(t) \) with the same value of \( \Sigma c_j \). These new functions aimed to resolve “the mystery” about the difference between the rich family of Lyapunov functions \( (j \)-divergences) for linear kinetics and a limited collection of Lyapunov functions for non-linear networks in thermodynamic conditions.

5. KB-self-organization of FC’s Based on QFI with QGA

The kernel of the abovementioned FC design toolkit is a so-called SCO implementing advanced soft computing ideas. SCO is considered as a new flexible tool for design of optimal structure and robust KBs of FC based on a chain of genetic algorithms (GAs) with information-thermodynamic criteria for KB optimization and advanced error back-propagation algorithm for KB refinement [5]. Input to SCO can be some measured or simulated data (called as ‘teaching signal’ (TS) about the modelling system. For TS design (or for GA fitness evaluation) we use stochastic simulation system based on the control object model. More detail description of SCO is given in [1,2]. Below we discuss the application of this algorithm in QFI structure.

5.1 Robust FC Design Toolkit

Figure 2 illustrates as an example the structure and main ideas of self-organized control system consisting of two FC’s coupling in one QFI chain that supplies a self-organizing capability. According to described above algorithm the input to the QFI gate is considered according (1) and Figure 4 as a superposed quantum state \( K_1(t) \otimes K_2(t) \), where \( K_{1,2}(t) \) are the outputs from fuzzy controllers FC1 and FC2 designed by SCO (see, in details Figure 4) for the given control task in different control situations (for example, in the presence of different stochastic noises).

The algorithm of superposition calculation is presented in Figure 12 and described in details in [5,6].

Figure 12. The algorithm of superposition calculation.

We discuss for simplicity the situation in which an arbitrary amount of correlation is unlocked with a one-way communication message [1,2]. The states exhibiting this behavior need not be entangled and corresponding communication can be organized using Hadamard transform [5-7]. Therefore, using the Hadamard transformation and a new type of quantum correlation as the communication between a few KB’s it is possible to increase initial information by unconventional quantum correlation (as the quantum cognitive process of a value hidden information extraction in on-line, see, e.g. Figure 5).

Let us consider a simplified case of QFI when with the Hadamard transform is organized an unlocked correlation in superposition of two KBs; instead of the difficult defined entanglement operation an equivalent quantum oracle is modelled that can estimates an “intelligent state” with the maximum of amplitude probability in corresponding superposition of classical states (minimum entropy principle relative to extracted quantum knowledge [5-7]).

Interference operator extracts this maximum of amplitude probability with a classical measurement.

Figure 13 shows the structure of Quantum Computing Optimizer of robust KB-FC based on QFI [5].

Using of described QFI model to control of non-linear locally and globally unstable dynamic systems below is described.
5.2 Benchmark’s Simulation of Smart Control with QFI

It is demonstrated that FCs prepared to maintain CO in the prescribed conditions are often fail to control when such a conditions are dramatically changed. We propose the solution of such kind of problems by introducing a quantum generalization of strategies in fuzzy inference in on-line from a set of pre-defined fuzzy controllers by new QFI based systems. The latter is a new quantum algorithm in quantum computation without entanglement. Two Benchmarks are considered: robust control of locally and globally unstable control objects.

5.2.1. Benchmark 1: Globally Unstable Control Object Simulation

“Cart - pole” control object is a non-linear dissipative system. This is a typical task of control theory, they demonstrating quality of control system. Task of control is the stability of inverted pendulum in vertical position. The motion of the dynamic system “cart - pole” is described by the following equations

\[
\ddot{\theta} = \frac{g \sin \theta + \cos \theta \left( u + \xi(t) + a_2 \dot{z} + a_3 z - ml(\dot{\theta}^2 \sin \theta - \dot{\theta} \cos \theta) \right)}{m_c + m} \left( \frac{4}{3} \frac{m \cos^2 \theta}{m_c + m} \right) - k \dot{\theta}
\]

where \( \dot{\theta} \) is the pendulum deviation angle (degrees); \( z \) is the movement of the cart (m); \( g \) is the acceleration of gravity (9.8 m/s^2); \( m_c \) is the pendulum mass (kg); \( l \) is the pendulum half-length (m); \( \xi(t) \) is the stochastic excitation; and \( u \) is the control force acting on the cart (N). The equations for the entropy production rate in the control object and the PID controller have the following form, respectively:

\[
\frac{d}{dt} S_p = k \dot{\theta}^2 + \frac{ml \dot{\theta}^2 \sin 2\theta}{m_c + m}; \quad \frac{d}{dt} S_z = a_2 \dot{z}^2;
\]

\[
\frac{d}{dt} S_\theta = k_\theta \dot{\theta}^2 \quad (51)
\]

The following parameter values are determined: \( m_c = 1; m = 0.1; l = 0.54k = 0.4; a_1 = 0.1; a_2 = 5 \); and the initial position \( [\theta_0; \dot{\theta}_0; z_0; \dot{z}_0] = [10; 0.1; 0; 0] \) (the value of the pendulum deviation angle is given in degrees); the constraint on the control force is -0.5 < \( u \) < 5.0.

The specific feature of control problem for the given control object (50) is the application of one fuzzy PID controller for controlling the movement of the cart (with one degree of freedom), while the control object has two degrees of freedom.

The control goal is that the pendulum deviation angle (second generalized coordinate) reaches the given value via the implicit control using the other generalized coordinate and corresponding essentially nonlinear cross-connections with the cart movement coordinate (effect of energy transmission between the generalized coordinates).

In the case of the similar initial learning conditions, the SCO with soft computing is used to design KB1 of FC1 for the generalized criterion of minimal mean square error:

\[
\int_{t_0}^{t_e} \theta^2(t) dt + \int_{t_0}^{t_e} \dot{\theta}^2(t) dt
\]

and KB2 for FC2 for the generalized criterion of minimal absolute error of the pendulum position:

\[
\int_{t_0}^{t_e} |\theta(\tau)| d\tau + |\dot{\theta}(\tau)|
\]

Thus, we consider the solution of the vector (multi-objective) optimization problem based on the decomposition of the KB. The Gaussian noise was used as the random signal for designing KB1, and Rayleigh noise was used for forming KB2 (see Figure 14, learning situations (S1, S2), respectively).

Figure 14. Random noise used in situations (S1, S2)

Physically the first criterion is equivalent to the total energy of the overturned pendulum and the second criterion characterizes the precision of the dynamic behavior of the control object.
Figure 15 shows KB1 and KB2 with the corresponding activated numbers of rules equal to 22 and 33 for a total number of rules of 729.

**Figure 15.** Form of KB1 and KB2 with corresponding activated production rules

Two contingency control situations (S3, S4) were simulated; in one of them (S3) the new noise $\xi(t)$ was introduced, the random signal with uniform one dimensional distribution, the control error signal delay (0.03s), and the noise signal in the position sensor of the pendulum (noise amplification coefficient 0.015).

Figure 16 shows the example of operation of the quantum FC for formation of the robust control signal using the proportional gain in contingency control situation S3.

**Figure 16.** Example of operation of the block of KB self-organization based on QFI

In this case, the output signals of KB1 and KB2 in the form of the response on the new control error in situation S3 are received in the quantum FC. The output of the block of quantum FC is the new signal for on line control of the factor $k_p$.

Thus, the blocks of KB1 and KB2, and quantum FC in Figure 2 form the block of KB self-organization in the contingency control situation.

Figure 17 shows the dynamic behavior of the studied system “cart - pole” and the control laws of the self-organized quantum controller (QFI), FC1 and FC2.

**Figure 17.** Dynamic motion of pole in situation S3

Remark. The following notation is used in Figure 12 and below: $\theta = \theta$ is the angle of pendulum deviation from the given position; $z$ is the cart position; the quantum FC is based on the spatial correlation.

The results of simulation (Figure 17) demonstrate that the dynamic CO in contingency / unpredicted control situations (S3) for the control of FC1 (FC2) loses stability, and for the control of quantum FC the control system possesses the property of robustness and achieving the control goal is guaranteed. According to the results of simulation (Figure 17), the required amount of control for the given criteria in contingency control situations (S3) for the control of FC1 and FC2 also is not achieved, while in the case of control of the quantum FC the control system possesses the required amount of control.

This yields that two non - robust fuzzy controllers can be used to design in on line the robust fuzzy controller using quantum self-organization; the KB of this robust FC satisfies both quality criteria.

Therefore, the decomposition of the solution to the above multi-objective optimization problem for the robust KB in the contingency control situation into partial solutions to optimization sub-problems physically can be performed in on line in the form of separate responses of the corresponding individual KBs optimized with different fixed cost functions and control situations. The aggregation of the obtained partial solutions in the form of the new robust KB is performed based on the quantum FC containing the mechanism of formation of the quantum correlation between the obtained partial solutions. As a result, only responses of the finite number of individual KBs containing limiting admissible control laws in the given contingency situations are used.

The control laws of variation of the gains of the fuzzy PID controller formed by the new robust KB have a simpler physical realization (see, Figure 16, right side col-
umn), and as a result they possess better characteristics of individual control cost function for the contingency control situation.

For experimental testing a physical model of robot (Figure 18) is used.

![Figure 18. Mobile robot configuration](image)

Three situations of control are tested.
- First situation images simple situation.
- The second situation use uniform noise in control channel, Gaussian noise in wheel friction and delay of control action — 0.01 sec.
- And the third situation has delay of control action equal 0.03sec.

Simulation and experimental results (for the complex situation 3) are shown in Figure 19.

PID controller as FC1 and FC2 do not reach the goal in unpredicted situation. But quantum FC based on these fuzzy controllers, successful in unpredicted situation. For experiments and modeling we use QFI with temporal correlation, between FC1 and FC2.

Thus, the output signal of the quantum FC represents the on line optimal control signal for variation of the gains of the fuzzy PID controller which includes the necessary (best) qualitative characteristics of output control signals of each of the fuzzy controllers with priority and dominating component among the control quality criteria.

![Figure 19. Control error. Unpredicted situation: (a) modeling; (b) experiment on physical model](image)

Therefore, the generalized self-organization principle \[1-7\] is realized.

5.2.2 Benchmark 2: Remote Rule Base Optimization

To compare method of remote rule optimization on the real control object with method using Matlab simulation for optimization we created 6 KB-FC.

| No | TS Source          | Optimization method         | Rule’s count |
|----|--------------------|------------------------------|--------------|
| FC1| Math. model        | Math. modelling              | 125          |
| FC2| CO (GA-PID)        | Math. modelling              | 125          |
| FC3| Math. model        | Remote connection            | 125          |
| FC4| CO (GA-PID)        | Remote connection            | 125          |
| FC5| Math. model        | Math. modeling + Remote connection | 125           |
| FC6| CO (GA-PID)        | Remote connection + Math. modeling | 125           |

Experiment and modeling were performed in two control situations. The first situation (S1) is typical for the control system (the initial angle equals to 1). The goal is to maintain the pendulum in equilibrium (0° angle of deflection). It should be noted that KB optimization held in this control situation. The second situation is unexpected (S2). The initial angle equals to 5°. This situation characterizes the perturbation caused by external influences on CO.

Figure 20 shows a comparison of integrals of squared
error for all regarded regulators in a typical situation of control.

![Figure 20. Integral square error. Typical situation: Simulation and experiment.](image)

The lower is integral square error level, the better controller works. Consider the results of simulation and experiment in unpredicted situation of control:

Figure 21 shows a comparison of integrals of squared error for all regarded regulators in an unpredicted situation of control.

![Figure 21. Integral square error. Unpredicted situation: Simulation and experiment.](image)

5.2.3. Benchmark 3: Remote Quantum Base Optimization

Let’s compare the PID controller, fuzzy controllers FC1 and FC4, and QFI controllers based on different correlations: Quantum-Space (Q-S), Quantum-Time (Q-T), Quantum-Space-Time (Q-ST). These QFI controllers are optimized using remote connection.

Mathematical modeling and physical experiments took place in two control situations:

- in the first (typical) situation (S1), the delay of control is standard as 0.015 sec;
- in the second unpredicted situation (S2), the delay of the control as 0.035 sec.

From Figure 22 and 23 it can be seen that KB optimization using a remote connection with quantum optimizer can improve the quality of control in a typical and unpredicted situation better than the application only the soft computing technology.

![Figure 22. Control error. Typical situation of control (Experiment)](image)

![Figure 23. Control error. Unpredicted situation of control (Experiment)](image)

Related works. Quantum computing approaching in robot path planning, emotion design, navigation, learning, decision making was applied also in [6,7,35,36] etc. Our approach is based on quantum self-organization of knowledge bases using responses of imperfect KB from fuzzy controllers on unpredicted situations in on line.

5.3 Benchmark’s Simulation of Wise Control with QFI Based on QGA

One of the interesting ideas was proposed in 2004, taking the first steps in implementing the genetic algorithm
on a quantum computer \cite{35,36}. The author proposed this quantum evolutionary algorithm, which can be called the reduced quantum genetic algorithm (RQGA).

The algorithm consists of the following steps: 1) Initialization of the superposition of all possible chromosomes; 2) Evaluation of the fitness function by the operator $F$; 3) Using Grover's algorithm; 4) Quantum oracle; 5) Using the diffusion operator Grover $G$; 6) Make an evaluation of the decision. The search for solutions in RQGA is performed in one operation.

In this case the matrix form is the result of RQGA action as following (see Figure 24).

![Figure 24. The result of the RQGA algorithm](image)

The overall strategy for improving the quality of QGA is to use small improvements in the algorithm. For example, including new operators: “quantum disaster”, disturbance, or other customized algorithms \cite{7}. But in many cases, these operators are only useful in highly specific applications.

5.3.1 Simulator Structure and Examples of Applications

The use of simulators has long been used in various industries: motor racing, aviation, surgery and many others. The development of virtual reality technology and augmented reality adds the ability to create simulators with full immersion. Most of the server side work is math. It is necessary to calculate the position of the carriage, the angle of inclination of the pendulum in space. For this reason, Python and the Django framework, which implements the model-view-controller (MVC) approach, were chosen as the programming language (or in Django, this is the model-view-template (MVT)). MySQL is used to store all data, and the architecture has been developed for adding Redis to be faster, if the MySQL operation speed is insufficient.

Figure 25 shows Benchmark results of quantum intelligent control simulation of “cart - pole” system with QGA (box for the type choice of “Quantum correlation” on Figure 4).

![Figure 25. The result of the QGA](image)

Temporal and spatial correlations have similar quality. After 5000 generations probability value is not changing. QGA after 200 generations the probability choice of spatio-temporal correlation decreases to 60% (see, Figure 26).

![Figure 26. The result of the quantum genetic algorithm 200 times](image)
Partial rendering performance of the simulator is shown in Figure 27. The described method is differed from others results described in [7,8].

Example: Application of quantum computing optimizer of knowledge base (QCOPTKB™) for the case of experimental teaching signal from control object. Control object shown in Figure 28a.

Example: Application of quantum computing optimizer of knowledge base (QCOPTKB™) for the case of experimental teaching signal from control object. Control object shown in Figure 28a.

Figure 28. Autonomous robot with inverted pendulum (a) and simulation & experimental results comparison for unpredicted control situation in cases of PID-controller, fuzzy controller and QFI-controller for “cart - pole” system and 7 DoF redundant robotic manipulator (b).

Structure of robust intelligent control system (ICS) based on QFI is shown in Figure 2 and on Figure 4 is shown QAG structure of QFI that used in the simulation and experiment. Figure 28b demonstrated results of simulation and experimental results comparison. Mathematical modeling and experimental results are received for the case of unpredicted control situation and knowledge base of fuzzy controller was designing with SW of QCOPTKB™ for teaching signal measured directly from control object (autonomous robot in Figure 28a, Box $Z^{-1}$ on Figure 2). As model of unpredicted control situation on Figure 2 (Box $Z^{-1}$) was the situation of feedback sensor signal delay on three times.

For robotic manipulator with 7 DoF result demonstrated on Figure 28b (right side) and the accuracy of quantum controller is more than ten thousand times higher of soft computing approach. It is the demonstration of quantum soft computing supremacy.

Results of controllers behavior comparison confirm the existence of synergetic self-organization effect in the design process of robust KB on the base of imperfect (non robust) KB of fuzzy controllers on Figure 28. In unpredicted control situation control error is dramatically changing and KB responses of fuzzy controllers (FC 1 and FC 2) that designed in learning situations with soft computing are imperfect and do not can achieve the control goal. Using responses of imperfect KB (as control signals for designing the schedule of time dependent coefficient gain in PID-controller on Figure 2) in Box QFI the robust control is formed in on line. This effect is based on the existence of additional information resource that extracted by QFI as quantum information hidden in classical states of control signal as response output of imperfect KB’s on new control error (QFI algorithm structure on line in Figure 4). QGA in Figure 5 for this case recommended the spatial quantum correlation as was early received in [1,2].

6. Discussion

The described design method of ICS based on QAG-approach let to achieve global robustness in the case of unpredicted control situations in online using new types of computational intelligence toolkit as quantum and soft computing and based on computational resource of classical computers. The introduced model of QFI is a new type of quantum search algorithm based on sophisticated structure of quantum genetic algorithm embedded in its structure. Such on an approach to the solution of robust control design problems of classical nonlinear control objects (in general globally unstable and essentially nonlinear) is considered as benchmark for effective application of developed design information technology of ICS [4, 6-8]. The results of simulation and experiment show unconventional (for classical Boolean logic) conclusion: from response of two non-robust imperfect KB of FCs in the structure of ICS on Figure 2 with new quantum search algorithm QFI based on QGA possible to design in online robust quantum FC.

With RQGA based on reduced Grover’s QSA used spatial quantum correlation between two coefficient gain schedules of FCs in Figure 2 and quantum self-organization of imperfect KBs in online effectively on classical standard chip realized and described on concrete example.
This synergetic information effect has pure quantum nature, used hidden in classical states quantum information as additional information resource and does not have classical analogy.

Remark. Figure 29 demonstrates one of new possible approaches to design intelligent cognitive control system applying quantum robotic communications and BCI-system as in case of a chess game with quantum - like decision making.

Figure 29. Prototype of hybrid intelligent cognitive control system with BCI and robotic quantum-like decision making systems

Future applications are correlated with the development of hybrid intelligent cognitive emotion control system as the cognitive control system based on “Brain - Computer Interface” (BCI) and quantum - like decision making models \(^{[57]}\) applying robotic - human interactions with quantum knowledge exchanging and communications as “brain-to-brain” and so on. These approaches apply quantum deep machine learning with quantum neural network and quantum genetic algorithms for designing the synergetic information control of intelligent robotic swarm with entangled states and knowledge exchanging, and free energy principle of human being emotion with minimum generalized entropy production \(^{[58]}\). In Part II of this article the applications of intelligent cognitive control system presented on Figure 29 discussed.

7. Conclusions

- Self-organized man-made intelligent port-controlled Hamiltonian systems are described as quantum control algorithm.
- Structure of QFI model \(^{[35]}\) based on QGA as the particular case of general quantum control algorithm of self-organization is introduced.
- Quantum supremacy of intelligent cognitive control with information-thermodynamic trade-off distribution \(^{[36]}\) of main control qualities for micro-nanorobotics demonstrated.
- New circuit implementation design method of quantum gates for fast classical efficient simulation of QAs is developed. Benchmarks of design application as Grover’s QSA and QFI based on QGA demonstrated. Applications of QAG approach in intelligent control systems with quantum self-organization of imperfect knowledge bases are described on concrete examples.
- The results demonstrate the effective application possibility of end-to-end quantum technologies and quantum computational intelligence toolkit based on quantum soft computing for the solution of intractable classical and algorithmically unsolved problems as design of global robustness of ICS in unpredicted control situations and intelligent robotics.
- Efficient simulation on classical computer quantum soft computing algorithms, robust fuzzy control based on quantum genetic (evolutionary) algorithms and quantum fuzzy neural networks (that can realize as modified Grover’s QSA), AI-problems as quantum gate simulation approaches and quantum deep learning, quantum optimization in Part II are considered.
- Thus, positive application results of mutual technologies based on soft and quantum computing give the possibility of application Feymann - Manin thesis to study classical physical system as inverse problem “quantum control system - classical control object” solve effectively classical intractable and algorithmic unsolved problems.

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Appendix 1. Interrelation between principles of maximum work value generation and minimum entropy production: Hamilton-Jacobi equation approach

Power of information-thermodynamic approaches for the analysis of dynamic systems demonstrated in many publications [8-12,17,24,37-55]. This Appendix 1 concentrate the attention on quantum supremacy of the extraction work from quantum hidden information that applied as the information-thermodynamic force in intelligent cognitive controllers embedded in the structure of smart control systems.

The definition principle of system maximal work generation is the following:

\[ W_{\text{max}} = \max \left\{ -\tau' L(T,\dot{T}) d\tau \right\} = \max \left\{ -\tau' \left( 1 - \frac{T'}{T + T} \right) f d\tau \right\} \tag{A1.1} \]

In (A1.1) the function \( L(T,\dot{T}) \) is a Lagrangian function of a dynamic system.

The alternative definition form of work is the functional as following:

\[ W_{[\tau',\tau']} = \frac{W}{G} = \int_{\tau'}^{\tau} c \left( 1 - \frac{T'}{T + T} \right) d\tau - \frac{T'}{2} \frac{\dot{T}^2}{T(T + T)} \tag{A1.2} \]

and

\[ S = \int_{\tau'}^{\tau} c \frac{\tilde{T}^2}{T(T + T)} d\tau \tag{A1.3} \]

Thus, problems of the maximum released work is equivalent to the associated problem of the minimum entropy production and have the same solutions. The characteristic function

\[ I(\tau', T', \tau', T') = \max W_{[\tau',\tau']} = \max \left\{ -\tau' \left( 1 - \frac{T'}{T + T} \right) f d\tau \right\} \tag{A1.4} \]

control the maximum work delivery. It is clear that the quantity \( I \) in Equation (A1.4) describes the extremal value of the work \( W(T', T') \) of Equation (A1.1) as following:

\[ W_{\text{max}} = \max \left\{ -\tau' L(T,\dot{T}) d\tau \right\} = \max \left\{ -\tau' \left( 1 - \frac{T'}{T + T} \right) f d\tau \right\} \tag{A1.5} \]

whose extremal value is the function \( I(T', \tau', T', \tau') \).

The Hamilton-Jacobi equation for the maximum work problem has described as

\[ \frac{\partial I}{\partial \tau} + H \left( T, \frac{\partial I}{\partial \tau} \right) = 0 \]

\[ H \left( T, \frac{\partial I}{\partial \tau} \right) = c \left[ \sqrt{T'} - \sqrt{T} \left( 1 - \frac{1}{c} \frac{\partial I}{\partial \tau} \right) \right] \tag{A1.6} \]

Therefore, the variational front-end problem for the maximum work \( W \) is equivalent to the variational fixed-end problem of the minimum entropy production.

Example: Thermodynamic work extraction with information gain. During the isothermal expansion, work is performed by the particle while moving the barrier (which could be extracted by e.g. attaching a pulley and weight to the barrier). The total work performed during the isothermal expansion is given by

\[ W_{\text{esp}} = \int_{\tau/2}^{\tau} k_s T dV = k_s T \log 2 \]

and this work is gained by a full conversion from heat energy to work. Conservation of energy shows that, since the initial and final state is identical with the same energy, \( W = -Q \). If the heat capacity of the environment was not infinite, the work extracted per cycle would be smaller than \( k_s T \log 2 \) since the final state would have lower energy than the initial one. Nevertheless, by continually repeating the process the heat bath would eventually be completely drained of energy, all of which would be converted to useful work. Szillard emphasized the necessity of performing a measurement for the engine to work. He connected the apparent violation of the second law with the state of the demon’s knowledge, and believed that their solution to the paradox was due to some hidden entropic cost associated with the measurement.

There are three main approaches to explain the apparent violation of the second law that Maxwell’s demon and the Szillard engine implies.

1. The first approach focuses on the role of fluctuations, which are usually ignored in the idealized thought-experiments but will always be present in real systems.

2. The second approach follows Szillard’s own belief and focuses on the entropic cost of performing measurements.

3. The third approach focuses on the fact that the demon has to store the information it obtains about the system. Unless this information is deleted, the final state of the universe will not be identical to the initial state. The third approach focuses on the cost of deleting this memory.

The second law of thermodynamics places constraints on state transformations. A proper definition of the second law of thermodynamics is that entropy cannot spontaneously decrease when averaged over a suitable timescale. What constitutes a suitable time-scale depends on the relaxation time of the system in question and is difficult to define in a general way. A quantitative description of the connection between fluctuations and the second law was given in 1993, when Evans et. al introduced the fluctuation theorem. The theorem is actually a group of closely connected theorems, one of which relates the probability of observing a time-averaged entropy production of magnitude \( \Delta S \), to the probability of that it takes the opposite value \( -\Delta S \) as following

\[ P(\Delta S) = \frac{P(-\Delta S)}{k_B} \exp \left\{ \frac{\Delta S}{k_B} \right\} \geq 1 \]

Since the right side is always
positive and larger than 1, the probability to observe fluctuations that temporarily "violate" the second law is always less or equal to the ones that obey it. Moreover, the relative probability of producing and consuming entropy increases exponentially with the amount of entropy change. Since entropy is extensive, the fluctuation theorem also shows that the probability to observe negative entropy fluctuations goes to zero for macroscopic systems.

If $Q$ is the average heat absorbed by the system under the transformation, the total entropy production (i.e., system + environment) is then given by

$$\Delta S_{\text{tot}} = (S_f - S_i) - \beta Q.$$ 

According to the second law of thermodynamics, total entropy change is bounded below at zero

$$\Delta S_{\text{tot}} \geq 0 \rightarrow \Delta S \geq \beta Q.$$ 

A physical process which achieves equality in this bound, is considered a thermodynamically reversible process. Notice that the flow of entropy between system and bath is possible for reversible processes, if the amount of heat absorbed by the system is equal to its entropy change. This is because the absorption of heat by the system results in a decrease in the environment entropy according to

$$S_{\text{env}} = -\beta \ln \rho.$$

Example: Quantum thermodynamic force and work extraction. It is known that negative work $\Delta W$ can be extracted from an isothermal cycle with a feedback controller and due the measurement the change in the entropy of the system can be expressed as

$$\Delta S_{\text{meas}} = H(X|M) - H(X) = -I(X:M)$$

$\ln \rho(x)$ is the Shannon entropy and $I(X:M)$ is the mutual information between the state of the system and the measurement $M$ outcome. Thus, while the amount of mutual information $I(X:M)$ is positive then the controller causes the entropy of the system to decrease. It is means that the presence of the controller expected to lead to extracting more work from the system that what expected. The controller can be incorporated into the Second Law as the following

$$\Delta W \geq \Delta F - \frac{1}{\beta} I(\rho_1 : X)$$

$$+ H(\rho_1:X),$$

where $\rho_1$ is the state of the system at some time $t_1$, $s(\rho)$ is the von Neumann entropy, $H(p_i) = -\sum p_i \ln p_i$ is the Shannon entropy content and

$$H(\rho_1:X) = -\sum_i \text{Tr} \left[ D_i \rho_i \sqrt{D_i} \ln \sqrt{D_i} \rho_i \sqrt{D_i} \right],$$

$$(D_i) = M_i^\dagger M_i,$$

are positive operator value-measure. The time derivative of these three terms give the result for extraction of work with controller as following:

$$\frac{dW_{\text{meas}}}{dt} = \frac{1}{\beta} \text{Tr} (\rho_1 \ln \rho_1) + \sum p_i \ln p_i - \sum_i \text{Tr} \left[ D_i \rho_i \sqrt{D_i} \ln \sqrt{D_i} \rho_i \sqrt{D_i} \right].$$

Thus, there are three quantum thermodynamic forces responsible for the extra work done during the process. Since the work is given by the change in the internal, we can obtain

$$W = \Delta F(\alpha) + \alpha^{-1} D_{\text{El}} \left[ \rho_1 \| \rho_{\text{can}}(\alpha) \right] - \alpha^{-1} D_{\text{El}} \left[ \rho_0 \| \rho_{\text{can}}(\alpha) \right],$$

where an inverse temperature as $\alpha$, the conservation of the Gibbs-Shannon entropy in a thermally isolated Hamiltonian system apply, i.e.,

$$S(\rho_1) = S(\rho_0)$$

and

$$\Delta F(\alpha) = F_{\alpha}(\alpha) - F_0(\alpha)$$

is the change in the Helmholtz free energy of the system. Work inequality can be achieved as:

$$W \geq \Delta F(\alpha) - \alpha^{-1} D_{\text{El}} \left[ \rho_1 \| \rho_{\text{can}}(\alpha) \right] = W_{\text{lb}}(\alpha),$$

where the lower bound for the work denoted as $W_{\text{lb}}(\alpha)$. Thus, there exists a best value for $\alpha$; namely, the value for which $W_{\text{lb}}(\alpha)$ is a maximum.
ARTICLE

Connected and Autonomous Vehicles (CAVs) Challenges with Non-motorized Amenities Environments

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ABSTRACT

With the deployment of Connected and Automated Vehicles in the coming decades, road transportation will experience a significant upheaval. CAVs (Connected and Autonomous Vehicles) have been a main emphasis of Transportation and the automotive sector, and the future of transportation system analysis is widely anticipated. The examination and future development of CAVs technology has been the subject of numerous researches. However, as three essential kinds of road users, pedestrians, bicyclists, and motorcyclists have experienced little to no handling. We explored the influence of CAVs on non-motorized mobility in this article and seven various issues that CAVs face in the environment.

1. Introduction

For more than a century, the automotive industry has existed. The intelligent process in the automotive area has accompanied in an era of fast growth in recent centuries, with the fast growth of science and technology. At this point, active safety technology has progressed, and while not all intelligent aided driving technologies have been implemented on a big scale in existing passenger cars, they will empower innovative adaptable systems that improve transportation protection and competence\textsuperscript{[1,2]}. A few alternatives for assisted driving include electronic stability, aggressive braking, and lane departure and retention systems. Despite technological advancements, road accidents continue to occur. More than 93 percent of all traffic accidents are still caused by driver error\textsuperscript{[3]}. At the moment, drivers have complete control of vehicles: they receive information, make verdicts, and lastly take accomplishment through a multifaceted process of insight and response to react to various road risks, and people must learn a lot more about autonomous vehicles\textsuperscript{[4,5]}. Vehicle safety systems, both passive and active, can still not fulfill the present aim of zero fatalities and accidents\textsuperscript{[6-9]}.

2. Literature Review

Due to advancements in sensor technologies, information technologies, and vehicle control technologies,
the automation of vehicle control has garnered a lot of attention recently. Intelligent traffic forms with self-driving technology have become an important aspect of addressing severe traffic safety, efficiency, and convenience challenges. Major automakers, Internet corporations, universities, and research organizations have all launched prototype or concept versions of CAVs. Recent statistics indicate that [6] Audi, BMW, Mercedes-Benz, Volvo, and other automobile manufacturers, as well as internet businesses like Baidu and WAYMO and public transit companies like Uber, have already put autonomous prototypes to the test and deployed the intelligent automotive market [7-9]. Simultaneously, the driverless test area for CAVs is improving; examples include the Detroit M-city in the United States, Shanghai Nice-city in China, and Chongqing’s I-Vista. Governments are also pushing autonomous technologies, with California allowing CAVs on public roads [10]. Beijing, China, has just made several roads available for testing self-driving cars. Shanghai also enables autonomous vehicles to operate on certain of the city’s partially open roadways, advancing linked and autonomous vehicles [11].

The introduction of CAVs sparked debate about coexistence with other road users, such as traditional automobiles and non-motorized traffic. Pedestrians and bikers are excellent indicators of a community’s social, economic, and physical well-being. In society, high levels of pedestrian and bicycle activity are frequently connected to stronger economies and healthier, more socially cohesive communities. A lack of pedestrian and bicycle activity on roadways, on the other hand, may indicate that personal security and safety needs aren’t being addressed, or that destinations aren’t accessible by foot or bicycle. On the other hands, the high number of automobiles on the road has risen year after year, eroding the space available for walking and bicycling and worsening the travel environment. Encourage and promote a high level of service for pedestrians and bicycles to improve fitness, clean air, and sustainability, and Automobiles emit plenty of pollutants into the atmosphere.

3. The Meaning of Connected and Autonomous Vehicles (CAVs)

Before getting into CAVs, it is important to understand the terms Automated Driving System (ADS) and Advanced Driver Assistant System (ADAS) [12]. More than a warning function is available in the ADS system. It also has a property for planning and controlling autonomous driving assistance systems. ADAS collects data, identifies static or dynamic objects, detects and tracks static cars, and combines that data with navigation map data using a range of sensors fitted in the vehicle. Drivers can receive alerts in advance while in an emergency, thanks to ADAS calculations and analysis. As a result, ADAS efficiently improves the vehicle’s driving comfort and safety. The system could actively intervene, such as activating the automated braking system, with the newest ADAS technology. CAVs are graded on 0 to 5, with 0 being the least automated and five being the most automated. The definitions for these six levels can be found in Table 1 [13]. The ADAS system refers to Level 0 to Level 2, and the ADS system refers to Level 3 to Level 5. Table 1 describes the driving levels.

| No  | Description                                                                 |
|-----|----------------------------------------------------------------------------|
| Level 0 | No automation                                                              |
| Level 1 | Automated systems can sometimes support the human in some parts of the driving activities. |
| Level 2 | Partially automated systems can conduct some driving activities while human monitors and accomplishes other driving activities. |
| Level 3 | Conditionally automated systems can demeanor some driving tasks in different situations, but the human driver must be ready to take back control |
| Level 4 | Highly automated can conduct all driving activities in different circumstances without human control. |
| Level 5 | Fully automated systems can perform all driving activities under all conditions in which humans could drive. |

3.1 Connected Vehicles

The goal of linked vehicles is for the vehicle to deliver relevant information to the driver to aid in decision-making, such as weather, a driver with a mobile phone that provides information to the urban traffic network or an in-car satellite navigation system that can provide real-time route information. As a result, the distinction between vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication is frequently noted [15]. It is worth noting that the car does not make decisions for it; instead, it communicates with the outside world to gather useful data. This technology used to be associated with automobile communication. It is becoming common for it to include the Internet of Vehicles. The Internet of Cars offers real-time networking between vehicles and roads, vehicles and other vehicles, vehicles and people, and vehicles and
the environment, as shown in Figure 1. It’s a network system that keeps track of, schedules, and controls the system’s various components. The Internet of Vehicles collects data from the vehicle’s sensing device (sensing layer). It uses network sharing (network layer) to connect drivers, pedestrians, the car networking platform, and the urban network, allowing for intelligent, safe driving and enjoyment of technologies and living services (application layer).

Figure 1. A representation of connected vehicles and infrastructure [16]

3.2 Autonomous Vehicles

Autonomous cars employ an inbuilt sensor to monitor their status and surroundings, then control their speed and direction using an actuator. To make decisions, the perception devices employ the path, vehicle location, and obstacle data they have collected. It’s a comprehensive intelligent system that incorporates navigation, environmental awareness, control, decision-making, and interaction into one package. Human-computer interaction models, sensor equipment, and algorithms are all part of the autonomous vehicle development process. A unified interactive platform does not exist now. Self-driving cars work in a fairly closed manner today, with no connection to the Internet of Things.

4. CAVs Control Optimization at Intersections in Urban Areas

What will happen to the city if people no longer have to drive when they pass through? As a result of this trend, communities must think about how autonomous vehicles can fit into their plans. According to traffic managers, highways may get narrower in the future. Furthermore, because people do not need to park vehicles, there will be more space on the main road for walking and cycling where parking meters used to be. It is possible that CAVs will not even have their specific area. CAVs can switch to different services at different times of the day thanks to share mobility with the Internet of Vehicles. A centralized intersection controller accepts vehicle requests. Calculate and verify vehicle conflict points by establishing the passing sequence of all vehicles, which must adhere to the principle of first-come, first-served [17], as shown in Figure 2.

Many low-level CAVs could handle driving on freeways and suburban roads, but urban road technology is
still inadequate, particularly in areas with congested traffic. Urban roads are more complicated than other roads, with many cars and various vehicle types. Various parts, non-motorized traffic flows, and road intersections all have vastly different speeds. As a result, the main challenge for self-driving automobiles in urban contexts is a technical one.

5. Connected and Autonomous Vehicles (CAVs) Issues

CAVs have made significant advances in all areas over the last few decades. New challenges and problems have surfaced at the same time. Multiple mishaps using CAVs, in particular, have prompted more critical and objective conversations concerning the impact of CAVs [19]. CAVs have experienced hurdles and obstacles in the following six areas: technology, safety concerns, legislation and policy, economy, privacy and cyber-security, and public acceptance.

5.1 Technology

Sensors, sensor fusion, localization, motion planning, and decision making are the three primary components of CAV-related technology [19]. CAVs use sensor equipment to recognize their surroundings, including pedestrians, traffic signals, and road signs. Vehicles should be able to decide whether to proceed or stop after receiving the data. Computer vision and machine learning are linked technologies. The perception process using sensor devices has made tremendous progress in recent years due to the popularity of deep learning technology, so the accuracy of identifying other road users and facilities has improved subversively [20]. This technology lays the groundwork for self-driving vehicles to be as safe as possible. Sensors, on the other hand, are now unable to recognize small-scale road signs or pedestrian movement. Identifying pedestrian behavior and predicting their intents, particularly for gestures, are the challenges [21]. Whether using laser, sonar, or radar sensors, the signals conveyed have a lot of noise and uncertainties in the second portion of sensor fusion and localization. The primary issues are how to filter out useless data and restore the objective environment in 3D. Particle Filter and Kalman Filter are two extensively used algorithms for localization. Radar and sonar were the primary sensors utilized by autonomous vehicles in the beginning. LIDAR, a revolutionary method that uses light for detection and ranging, has become popular in recent years (equipped with laser beams to illuminate at different times and spaces to get information), great penetration rates, quick perceptions, and high accuracy are all advantages of this technology [12,22]. LIDAR technologies, on the other hand, respond to a high price. Cost is a stumbling block for the mass manufacture of CAVs with LIDAR systems.

Furthermore, the concept of the Internet of Vehicles as it relates to CAVs faces technological challenges. Vehicle to Vehicle (V2V) communication is a flexible and convenient communication on the Internet of Vehicles that does not require coordination or control of basic communication infrastructure. As a result, V2V has good scalability. However, the distance of the work zone varies dramatically with time due to the vehicle's greater traveling speed. As a result, vehicle-to-vehicle network communication has drastically decreased. Vehicles will be segregated when coping with low traffic density. A high traffic density, on the other hand, will reduce network data transmission efficiency and accuracy. The Vehicle to Roadside (V2R) communication mode necessitates using a stationary communication device at the roadside. The network's scalability suffers as a result. As a result, this communication mode is suited for use in urban traffic scenarios that require many hotspots and base station signals.

5.2 Safety and Crashes

The numbers for traffic accidents in the United States in 2010 are shocking: 32,999 people were killed, 3.9 million people were injured, and 24 million vehicles were damaged, costing $277 billion in both real and intangible damages [23] and Nearly 80% of carbon monoxide emissions and 55% of nitrogen oxide emissions are attributed to transportation, according to the US Environmental Protection Agency. Bicyclists who commute to work save 2,000 miles of driving and around 2,000 pounds of CO₂ per year in the United States. Furthermore, it equates to a nearly 5% reduction in the average American carbon footprint. Furthermore, it corresponds to a nearly 5% reduction in the average American carbon footprint [24]. Pedestrians and bicyclists, on the other hand, are in a weak position in the urban transportation system when it comes to traffic safety issues and is more prone to traffic accidents [25], as Figure 3 demonstrates, the burden cost on the market has a ripple effect and affects productivity [26].

5.3 Economy

According to the estimate, it will take at least 2045 for half of the new vehicles to be autonomous and 2060 for half of the vehicle fleet to be autonomous, implying that CAVs will disrupt the current economic sector [28]. Traditional automakers’ business models have shifted as a result of driverless car technology. It improves communication between manufacturers and governments by determining...
if governments should provide automobile manufacturers sufficient authority to produce CAV peripheral products (infrastructures). Governments will also confront fiscal concerns, such as whether substantial sums of money are required to establish roads entirely for driverless automobiles to develop autonomous cars. Furthermore, the majority of current CAVs researches use sustainable energy, which has impacted fuel markets. According to estimates from Intel Corporation and Strategy Analytics, the economic effects of self-driving cars will total $7 trillion by 2050 (Figure 4). This outcome is based on the assumption that by 2025, all cars will be CAVs with a level 5 of automation [29].

6. Non-motorized Environment and Non-motorized Transport Amenities

Nonmotorized transportation provides fundamental mobility, affordability, public transportation access, and health benefits. Improving the convenience, comfort, and safety of walking and cycling helps to address the major traffic difficulties that many communities face. Walking and cycling are important contributions to lowering damaging local pollutants and greenhouse gas emissions because they are zero-emission modes. A non-motorized transportation strategy aids in the development of a shared vision for the improvement of the walking and cycling environment. The plan can be used as a guide for specific initiatives like streetscape makeover or the adoption of an on-street parking management system. It can also aid coordination among the various authorities involved in the planning and management of non-motorized transportation systems. A non-motorized transport strategy can supplement mobility plans, which provide detailed guidance on specific mobility initiatives, by laying out the vision for an improved walking and cycling environment. The following are different city with high rate of non-motorized transport:

Communities that improve non-motorized travel conditions generally see considerable increases in non-motorized travel and corresponding automobile travel reductions [34,35]. Residents of a pedestrian-friendly community walked, bicycled, or took public transportation for 49 percent of work trips and 15 percent of nonwork journeys, respectively, 18 and 11 percentage points higher than residents of a comparable automobile-oriented community [36]. Morris (2004) discovered that those who live within a half-mile of a cycling trail are three times as likely to commute by bicycle as the national average. Another study discovered that walking is three times more common in neighborhoods with pedestrian-friendly roadways than in less pedestrian-friendly streets [37]. As seen in Figure 5, non-motorized travel accounts for a significant share of travel in some cities.

If all other factors are equal, each mile of bikeway per 100,000 residents boosts bicycle commuting by 0.075 percent [38]. Although bicycles account for only around 1% of
all journeys in the United States, riding rates are five to 10 times higher in many North American localities (Comsis, 1993). As shown in Figure 6, international researchers have discovered considerable disparities in non-motorized travel habits. High levels of non-motorized travel in such geographically diverse regions, compared to lower levels in similar places, suggest that transportation regulations and community attitudes are more important in influencing non-motorized travel than geography or climate.

Figure 5. European cities have high rates of non-motorized transport

![Graph showing non-motorized transport in European cities]

Figure 6. Non-motorized travel common in some urban areas

7. Conclusions

The definition and newest developments in autonomous vehicles are discussed, and the obstacles and arguments that contemporary CAVs face, technical impediments the Internet of Vehicles' popularity, identity, and decision-making. We go over the definition of self-driving vehicles, how autonomous driving is classified, and the special equipment and technology required. The definition of connected and autonomous vehicles, as well as automotive networking, is fraught with debate. Some argue that the Internet of Automobiles does not apply to linked and autonomous vehicles. Many incidents involving self-driving vehicles have occurred worldwide due to technological flaws, resulting in fatalities. CAVs may have a big economic influence in the future, since the traffic system will be more efficient as a result of the benefits of the CAVs' following mode, which may improve fuel efficiency to some extent. The situation similarly raises the question of whether automakers have the legal right to build and operate infrastructure.

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ARTICLE
Quantum Algorithm of Imperfect KB Self-organization. Pt II: Robotic Control with Remote Knowledge Base Exchange

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The technology of knowledge base remote design of the smart fuzzy controllers with the application of the "Soft / quantum computing optimizer" toolkit software developed. The possibility of the transmission and communication the knowledge base using remote connection to the control object considered. Transmission and communication of the fuzzy controller’s knowledge bases implemented through the remote connection with the control object in the online mode apply the Bluetooth or WiFi technologies. Remote transmission of knowledge bases allows designing many different built-in intelligent controllers to implement a variety of control strategies under conditions of uncertainty and risk. As examples, two different models of robots described (mobile manipulator and (“cart-pole” system) inverted pendulum). A comparison of the control quality between fuzzy controllers and quantum fuzzy controller in various control modes is presented. The ability to connect and work with a physical model of control object without using than mathematical model demonstrated. The implemented technology of knowledge base design sharing in a swarm of intelligent robots with quantum controllers. It allows to achieve the goal of control and to gain additional knowledge by creating a new quantum hidden information source based on the synergetic effect of combining knowledge. Development and implementation of intelligent robust controller’s prototype for the intelligent quantum control system of mega-science project NICA (at the first stage for the cooling system of superconducted magnets) is discussed. The results of the experiments demonstrate the possibility of the ensured achievement of the control goal of a group of robots using soft / quantum computing technologies in the design of knowledge bases of smart fuzzy controllers in quantum intelligent control systems. The developed software toolkit allows to design and setup complex ill-defined and weakly formalized technical systems on line.

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Quantum algorithm
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1. Introduction: Self-organized Smart Control in Advanced Intelligent Robotics

The PID controller is distinguished as the most common form of feedback: more than 95% of the control feedback-loops are of PID type. These controllers can be found in all areas where control is used. Despite its straightforward structure, the popularity of PID controllers lies in the simplicity of the design procedures and in the effectiveness obtained to the system performance. Therefore, the beauty of the proportional-integral-derivative (PID) algorithm for feedback control is in its nature simplicity and efficiency. Those are the main reasons why PID controller is the most common form of feedback. PID – controller combines the three natural ways of taking into account the error: the actual (proportional), the accumulated (integral), and the predicted (derivative) values. The mentioned three gains depend on the magnitude of the error, the time required to eliminate the accumulated error, and the prediction horizon of the error. Those are the main reasons why PID controllers have survived many changes in technology, from mechanics and pneumatics to microprocessors via electronic tubes, transistors, integrated circuits, among others and applied as executive control level in projects [1] of “Industry 4.0” with Industrial AI.

Remark. The advent of the Industry 4.0 initiative has made it so that manufacturing environments are becoming more and more dynamic, connected but also inherently more complex, with additional inter-dependencies, uncertainties and large volumes of data being generated. Recent advances in Industrial AI have showcased the potential of this technology to assist manufacturers in tackling the challenges associated with this digital transformation of Cyber-Physical Systems, through data-driven predictive analytics and capacity to assist decision-making in highly complex, non-linear and often multistage environments. However, the industrial adoption of such solutions is still relatively low beyond the experimental pilot stage, as real environments provide unique and difficult challenges for which organizations are still unprepared. A set of key challenges and opportunities to be addressed by future research efforts are formulated along with a conceptual framework to bridge the gap between research in this field and the manufacturing industry, with the goal of promoting industrial adoption through a successful transition towards digitized and data-driven conventional controllers on executive control levels.

Actually, practically all PID controllers made today are based on microprocessors, so this nanoelectronics element has had a dramatic influence on this kind of control providing PIDs additional advances features for “Industry 4.0”, such as gain scheduling, continuous adaptation, and automatic tuning. The quantum self-organization algorithm model of wise knowledge base design for hybrid intelligent fuzzy PID - controllers with required robust level considered in [2-3].

Problems of advanced control system design. From the advanced control engineering point of view, improving system robust behavior is the major concern. To that end, the generalization of classical PID controllers to non-integer orders of integration and differentiation was proposed. Intuitively, with this extension of classical PIDs there are more tuning parameters and, consequently, more flexibilities in adjusting time and frequency responses of the control system. This also translates in more robustness in designs. However, the first step when applying an existing or new controller is to understand exactly what their actions can do in closed-loop in order to take full advantage of the possible effects on the system response. In the case of integer order, the interpretation of the three actions of PIDs seems to be clear: the proportional action is simply proportional to the current control error; the integral action is related to the past values of the control error, so represents the accumulated error, i.e., the area under the error curve; the derivative action predicts future values of the error or, in other words, corrects based on the rate of change of the deviation from the set-point.

The key aspect when tuning PID controllers is in deciding how to best combine those three terms to achieve the most efficient regulation of the process variable for the considered problem. As well known, the most obvious way is to use a simple weighted sum where each term is multiplied by a tuning constant or gain, and the results are then added together as follows: A new design of $n^{th}$ order binomial filters has shown that an appropriately tuned filtered PID control may yield faster closed-loop transients by producing a less excessive control effort than an optimally tuned PI control. These made it possible to deal, for example, with controllers using higher order derivative actions and to show them attractive also in control of the time-delayed systems. Physically, as example, PIDD controllers offer position, velocity and acceleration feedback useful in dealing with systems not allowing rapid output changes, when the loop behavior depends significantly on the previous control history. Since an analytical optimal design of four parameters of a PIDD controller, which, in addition, requires appropriate implementation filters to represent a highly complex problem, different alternative approaches as, for example, the particle swarm optimization have been tested.

Different approaches to design of expanded conventional controller’s structures in [4-9] described. In compar-
ison with the much simpler PI control, which still attracts attention of the contemporary research, the design is yet more complicated also due to the fact that an increased speed of transients exhibits all modeling and tuning imperfections. This task is intractable problem in advanced control system design.

Figure 1 demonstrates the structure of information technology design of intelligent control systems based on quantum soft computing.

Background of the model representation is a new model of quantum inference based on quantum genetic algorithm [2]. Quantum genetic algorithm applied on line for the quantum correlation’s type searching between unknown solutions in quantum superposition of imperfect knowledge bases of intelligent controllers designed on soft computing toolkit. Disturbance conditions of analytical information-thermodynamic trade-off interrelations between main control quality measures (as new design laws) discussed. The smart control design with guaranteed achievement of these trade-off interrelations is main goal for quantum self-organization algorithm of imperfect KB. Sophisticated synergetic quantum information effect (autonomous robot in unpredicted control situations and swarm robots with imperfect KB exchanging between “master – slaves”) introduced. A new robust wise controller designed on line from responses on unpredicted control situations of any imperfect KB applying quantum hidden information that extracted from quantum correlation. Within the toolkit of classical intelligent control, the achievement of the similar synergetic information effect is impossible.

Physical interpretation of this new quantum supremacy effect in system of system engineering introduced. Benchmarks of intelligent cognitive robotic control applications considered. The role of information extremum and free energy principles in quantum self-organization imperfect KB of smart fuzzy controllers with imperfect KB discussed.

2. Problem Statement: Main Tasks

Under conditions of uncertainty or inaccuracy of the initial information, unforeseen situations or information risk, the conventional (using the principle of global negative feedback) and industry-wide PID controller often fails to cope with the control task. At the same time, there is no solution to the problem of the global robustness of the PID controller so far, despite the urgency of this problem. The application of fuzzy controller (FC) in combination with a PID controller led to the creation of hybrid fuzzy ICSs with different levels of intelligence, depending on the completeness and correctness of the designed knowledge base (KB). This allowed to improve the quality of control, but doesn’t completely solve the problem of robust control in unforeseen situations. The application of the soft computing technology (based on the genetic algorithms, neural networks and fuzzy logic) has expanded the areas of effective use of PID with FC by adding new functions in the form of teaching and adaptation.

The application of quantum computing technologies (based on quantum deep machine learning with quantum neural network and quantum genetic algorithms) finds the solution to the above mentioned problem of the global robustness of the PID controller so far, despite the urgency of this problem.

This article considered a network of loosely coupled groups of robots working together to solve tasks that go beyond individual capabilities, and individually the elements don’t implement the difficult task. Different and information nodes of such a system, as a rule, have a different level of computational intelligence (knowledge, algorithms, and computational bases) and various resources in designing. Each node should be able to modify its behavior depending on the circumstances, as well as to plan its communication and cooperation strategies with other nodes. Here the indicators of the level of cooperation are the nature of the distribution of tasks, the unification of various information resources and, of course, the possibility of solving a common problem in a given time [2,3]. Typical examples of the interaction of such robotic systems are the tasks of object recognition and manipulation, control when moving along an optimal trajectory, route planning, stabilization of dynamically unstable systems (for example, an inverted pendulum), control of multi-link manipulators, when implementing hierarchical and decentralized

Figure 1. Main steps of intelligent control system design.
control in a group of robots \[^{[10-18]}\].

In this work, to demonstrate the interaction of the robotic systems, the robot’s models were designed - inverted pendulum and mobile platform with navigation, manipulator and stereo vision system (see, Figure 2). The robot control systems operate on the basis of quantum fuzzy controllers that were developed using the technology presented below \[^{[19-21]}\]. In particular, solving the task of controlling executive mechanisms, electric motors in coordination control and navigation systems, are used, above mentioned conventional PID - controllers.

The developed intelligent toolkit as Quantum Soft Computing Optimizer (SCO) of Knowledge Base (QSCOptKB\(^{TM}\)) \[^{[19,22,23]}\] allowed to design robust KBs applying the solution of one of the problems of the theory of artificial intelligence difficult to solve algorithmically - extraction, processing and formation of the objective knowledge without expert estimates.

Figure 2. A two-dimensional model of an inverted pendulum and mobile manipulator.

[here CO – control object, QFI – quantum fuzzy inference, ICS – intelligent control system]

In this SCO, three GAs are used that allow designing an optimal structure of a FC (the type and number of the MFs, their parameters, and the number of fuzzy inference rules), that approximates the teaching signal with the required error. In this case, the teaching signal can be obtained directly from the control object functioning in the learning mode. At the same time, an optimal structure of the fuzzy neural network is automatically designed and a model is formed of the universal approximator in the form of a fuzzy controller with a finite number of production fuzzy logic rules in the KB.

SCO on soft computing is a new effective software tool for KB design of robust ICS applying the presented criteria on the basis of information and thermodynamic measures of entropies. Structurally, SCO consists of interrelated genetic algorithms (GA\(_1\), GA\(_2\), GA\(_3\)) that optimize individual components of KB \[^{[1]}\]. The basic optimization steps and the structure of the SCO are shown in Figure 3.

Figure 3. Main stages of the knowledge base design on Soft Computing Optimizer (SCO).

Block FC is the central element of the ICS (Figure 1) and generates control signals of the time-varying (control laws) gain factors, \((k_p, k_i, k_d)\) (coefficient gain schedule) of the PID controller, applied to stabilize an inverted pendulum, mobile platform control and manipulator control. The functional structure of the ICS with FC and SCO blocks on soft and quantum computing is shown in Figure 3.

At the same time, the sources of teaching signals (TS) are on the one hand the physical environment measured by sensors with the ability to influence it with actuators and translate the system into the required state; on the other hand, the information (including model) representation of individual systems functioning among themselves with the set accuracy of approximation.

Key stages of knowledge extraction from physically measured control signal and teaching with reinforcement are hardware and software implementation of such algorithm, which allows to extract and form KB of cognitive-intelligent controller, while connecting to the CO on all stages of KB design. In the process of knowledge extraction, the classification of input control situations and verification of control actions on the CO is carried out. The learning process itself causes the expenditure of physical resources and a decrease in the quality of control, by checking the various trajectories of control and commands, while the information environment forms the structure of the KB. Note that in the space of the formed solutions, all the features of the physical implementation of the system (noise, backlash, errors in the manufacture of parts and environmental conditions) are taken into account.
account. As a result, imperfect data in TSs - resource in the learning process is compensated by knowledge, formalized in the form of KB, while laying the accuracy and reliability of control in the learning situation, taking into account the physical characteristics of the system.

Modeling the behavior of the system, firstly, allows to expand the class of problems solved by increasing the number of simulated situations (changes in mass, friction, various kinds of noise sensors and modeling the influence of the environment), and secondly, provides the ability to search for optimal trajectories in given situations modeling. However, the previous process of verification and identification of the model, as well as the process of search and approximation of optimal trajectories in the KB, require significant computational resources and strongly depends on the level of complexity of the described system, its correctness, the number of structural elements and connections between them. Moreover, in the case of unforeseen situations not inherent in the KB ICS, the application of such an approach will cause significant time delays in the feedback loop, which is quite critical from the point of view of control of these systems.

Let us consider the problem of maintaining a constant pressure and in a liquid nitrogen collector on an experimental setup designed to control the manufactured superconducting (SC) magnets of the complex apply SCO based on soft computing and SCOptKB™ toolkit (Figure 3).

Example: Intelligent robust liquid nitrogen flow control system in the collector of a cryogenic plant for control of superconducting magnets.

By controlling the nitrogen supply valve, it is necessary to regulate the pressure and flow rate of nitrogen in the collector. The control loop status is monitored by a pressure sensor and a nitrogen level sensor. In this state of superconductivity, the magnet winding must be maintained at the equilibrium point of the permissible range of changes in current, temperature and magnetic field (Figure 4).

The SC magnetic element of the accelerator complex itself during the tests has the following features: heat gain due to eddy currents leading to heating of the core, heat gain from the walls and uneven cooling in the connecting nodes. These features of an individual magnetic element also impose the complexity of managing a group of similar elements.

The principle of intelligent control implies compensation for the uncertain and inaccurate parameters of a magnetic element existing in a real object through the use of soft and quantum computing technologies and taking into account the peculiarities of individual knowledge bases.

Table 1 shows the input data - indicators of the state of the system and output - parameters of the actuators controlled by an intelligent control system for the conditions of the state of nitrogen in the stand collection.

| Input data                                      | Output                                |
|------------------------------------------------|---------------------------------------|
| Nitrogen outlet temperature data                | Target valve flap position            |
| Inlet nitrogen temperature data                 | Valve rotation speed                  |
| Pressure level reference signal                 |                                       |
| Setpoint signal for nitrogen level in the collector |                                       |
| Data on the state of the nitrogen level in the collector (tank) |                                       |

The efficiency of pumping, cooling the magnetic element and maintaining the superconductivity regime depends, among other things, on the pressure in the cooling system, and therefore on the nitrogen pressure in the collector and its level. In this case, it is necessary to take into account the increase and decrease in the nitrogen consumption in the process of heating and cooling the magnetic element, taking into account the inaccuracy of the actuator (valve).

Figure 5 shows the control loop of the first level, implemented in the form of a proportional-integral-differential (PID) controller with adjustable control parameters ($K_p$, $K_i$, $K_d$). The choice of optimal control parameters depends both on the listed features in the implementation of a separate magnetic element, and when controlling a group of magnetic elements.

Let us consider an example of designing an ICS for pressure control in a storage tank with nitrogen of a test bench of a magnet factory. At the first design stage, the indicators and parameters set by the operator in the control system were recorded (Figure 5). Further, the most effective trajectories of valve control (operator actions) were selected from the point of view of maintaining the

![Figure 4. The region of the superconducting state of the magnet winding](https://doi.org/10.30564/aia.v3i2.3849)
Figure 5. Developed and implemented software and hardware components of the control system

Figure 6. ICS design technology and interaction with Tango-Control
required pressure level and nitrogen flow rate.

Based on these data, using soft computing software tools from Figure 3, a fuzzy controller was designed (Figure 6).

In Figure 7 below is a graph showing operator actions (blue line) and fuzzy controller (brown line).

**Figure 7.** Control action of the operator (V19) and fuzzy controller (FC19).

In general, at this stage, the work of the regulator was assessed as correct.

In Figure 8 the experimental graphs of the nitrogen flow rate and pressure in the storage tank in the process of testing the magnetic element demonstrated, respectively.

**Figure 8.** Nitrogen level in the storage tank

The studies carried out have shown that when regulating in the control mode of a fuzzy controller, the nitrogen flow rate decreases.

Consider the example of the process of designing an intelligent control system (ICS) of inverted pendulum, the possibility of creating an intelligent robust control system with an increased level of robustness due to the application of quantum computing technologies and various information resources in the process of extraction and formation of KB.

### 3. Information Technology Design of Intelligent Control System with Remote Connection to SCO & QC

Control of inverted pendulum position it’s a classical task of control theory (see Figure 9). A dynamic system has global dynamic instability; in the absence of a control force, an unlimited increase in the deflection angle occurs, i.e. the pendulum falls. The task of controlling the system is to, by acting on the trolley by means of a control force, hold (stabilize) the pendulum in a vertical position (the angle of deviation of the pendulum axis from the vertical should be kept close to 0 under changing environmental conditions).

The equations for entropy production rate are as follows:

\[
\dot{S}_\theta = \frac{k \dot{\theta}^2 + 1/2m l \dot{\theta} \sin 2\theta}{l(m_c + m)} \left[ 4 - \frac{m \cos \dot{\theta}^2}{m_c + m} \right] \quad \dot{S}_e = \frac{a_1}{m_c + m} z^2; \dot{S}_e = k_\varepsilon \phi^2.
\]

In Equation (1), \(z\) and \(\theta\) are generalized coordinates; \(g\) is the gravity constant (9.8 \(m/\text{sec}^2\)), is the mass of the cart, \(m\) is the inverted pendulum (called the "pole"), \(l\) is half the length of the pendulum, \(k\) and \(a_1\) the coefficients of friction in \(z\) and \(\theta\) respectively, \(a_2\) is the elastic force of the cart, \(\xi(t)\) external stochastic noise, and \(u\) is the control force.

The structure of the computer model "cart – pole" (inverted pendulum), made in the environment of modeling MatLab/Simulink, is shown in Figure 10.

This computer model is used to obtain a training signal and configure the KB using SCO. As a control model of this system, we will use the expression (1) to calculate the control effect. In accordance with this control scheme, we will use the PID controller in the global negative feedback loop.

The sequence of application of software tools, sources of training signals and the result of the stages of application of tools are presented in Figure 11. The technology of application of the quantum optimizer and quantum fuzzy inference (QFI) allows to combine into a single control system several KB obtained from various information sources, which allows to take into account both the physical features of the CO and the model representation of the system.

The model includes a PID controller, noise in the control and measurement system, as well as a unit that generates a signal for the controller.
Figure 9. Intelligent control system of inverted pendulum and mobile manipulator

Figure 10. Modeling system structure: 1-fuzzy output unit; 2-PID controller; 3-control object; 4-noise generators
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Figure 11. SCO & QO technology for designing robust ICS

The input of the SCO is a teaching signal (TS), which can be obtained either at the stage of stochastic simulation of the CO behavior (using its mathematical model), or experimentally, i.e., directly from the results of measurements of the dynamic parameters of the physical model of the CO. TS is a source of knowledge and is an array of data divided into input and output components, each of which, in turn, consists of one or more signals. If some control signal is approximated, the input components may be a control error, an error integral and its derivative, and the output component is the desired control action value, or some adjustable control system parameters, for example, the gain coefficient of the PID controller.

For Figure 12, the input data for FC is the error vector, which consists of the control error $e$ and the rate of change of the control error $\dot{e}$.

For Figure 12, the data for FC is the error vector, which consists of the control error $e(t)$, the integral of the control error $\int e(t) dt$, and the rate of change of the control error $\dot{e}(t)$.

Output data FC is a vector consisting of the values of the gain, $k_p$, $k_d$, $k_i$, PID controller, the values of which are used in the formation of the control action in the following form:

$$u(t) = k_p(t)e(t) + k_d(t)\int_0^te(\tau)d\tau + k_i(t)\dot{e}(t)$$  \hspace{1cm} (2)

Before proceeding with the design of the IC, it is necessary to verify the parameters of the mathematical model (1).

Table 2 presents the classification of defined and undefined parameters of the system model. The problem of finding undefined parameters can be solved on the basis of GA. The assumed ranges of undefined parameters are the boundaries of the search space for multi-criteria optimization. The chromosome of the algorithm consists of a vector of indeterminate parameters, and the initial population is randomly generated by the spread of chromosome’s carts the search space. GA selects a set of parameters of the mathematical model so that the dynamics of the mathematical model corresponds to the dynamics of the robot (for example, the error in the form of the difference between the signals from the mathematical model and the physical signal is minimal).

| Certain parameter | Undefined parameters |
|-------------------|----------------------|
| Mass of the pendulum | Friction in the axis of rotation |
| Mass of the carriage | Coefficient of elasticity of the carriage |
| Center of gravity of the pendulum | Backlash in the axis of rotation |
| Limitation on the control error | Normalizing coefficient of control action |
| The time for one cycle of the system | The noise of the measuring system |
| PID coefficients | Friction of wheels on the surface |
| Input and output data of technical product controller | |

The target function of the algorithm for verification can be based on the dispersion of information supplied to the input and received at the output of the controller or fuzzy controller.

In this case, the fitness function was used as a function of the form:

$$F(e,u) = \left[1 + \left(\frac{\text{Var}(e_{\text{mod}}) - \text{Var}(e_{\text{ex}})}{\text{Var}(e_{\text{mod}})}\right)^2 + \left(\frac{\text{Var}(u_{\text{mod}}) - \text{Var}(u_{\text{ex}})}{\text{Var}(u_{\text{mod}})}\right)^2\right]^{-1}$$

Where $\text{Var}(e_{\text{mod}})$ – variance of control error in the model,
\( Var(e_{\text{op}}) \) – variance of control error in operation, \( Var(u_{\text{rel}}) \)
\( mod() \) – dispersion of the control action in the model and layout, \( Var(i_{\text{rel}}) \)
\( Var(i_{\text{op}}) \) – variance of the integral of the control error model and layout, respectively.

It should also be noted that it is possible to use other fitness functions, for example, the integral of the difference between the points of the resulting sample graphs, etc.

After verification, the found parameters are substituted into the model, and then the coefficients for the PID controller are searched. To do this, use GA, the chromosome of which are gain, and the fitness function – the evaluation function of quality control the following:

\[
f(x_t) = \frac{1}{1 + \int_0^t e^2 dt},
\]

(4)

Where \( e \) is the value of the deviation from the master signal, \( t \) is the integration range equal to the test time of one solution. Next, the coefficients are tested on the layout according to the scheme in Figure 13.

**Figure 13.** Algorithm verification with the use of GA

In case of unsatisfactory result, it is necessary, if possible, to re-identify the system-to reduce or increase the number of undefined parameters by fixing one or more of them in the mathematical model, with a corresponding increase in the search space parameters.

The results of verification of the mathematical model and layout of the system, in the form of graphs of control errors are presented in Figure 14.

It is required to achieve a high level of suitability of the tested solution for verification. For this case, the algorithm finished with the value of the fitness function: \( \text{Fit} = 0.9847 \).

**Figure 14.** The angle of deviation of the robot and model

Further, on the basis of the verified model, including the selected undetermined parameters (control noise, noise intensity in the control, the coefficient of friction of the wheels on the surface, the coefficient of friction in the axis of rotation, the coefficient of elasticity, etc.) was designed KB.

4. Design Using System Layout

Consider the possibility of using GA-PID controller to obtain TS and further approximation of the signal on the neural network using SCO.

One of the disadvantages of GA is the inability to use in the future solutions that do not fall into the next generation. When documenting solutions, for a third-party observer of the algorithm, this data turns into a huge array of hard-to-process information.

For Figure 15 on the left is the TS with the layout in the form of a graph of the angle of deviation and changes in gain.

This signal is derived from the GA-PID controller. The presented data set of the learning process of the CO and the selected areas are "knowledge" about the gain and their changes. It is obvious that the information about the learning process of the robot contains knowledge (in terms of the selected quality criterion) about the suitability of the tested solutions.

It is important to note that the amount of this knowledge grows in the learning process. In the first generations (with a random distribution of chromosomes in the search space), this knowledge is minimal, but with the passage of time and the change of generations, the amount of useful information increases, and the quality of control increases. This data set contains information about both the possible States of the CO (deflection angle) and the gain for each time. Using the software tools SCO, it is possible to allocate knowledge from the signal obtained in the process of GA in online, with their further use in the KB FC.

Thus, the designed KB will contain knowledge about the physical features of the control object, backlash, noise, friction and implementation features. This type of training allows you to extract knowledge about poorly formalized
and poorly structured CO, for which it is difficult to design an adequate model.

It should also be noted the set clock cycle time of the system. For simulation and experiment, the duration of the cycle was taken constant during the tests and is 0.01 sec.

The result of genetic selection was a signal, part of which is shown in Figure 15. This signal is the input signal in the QFI.

The first three columns in Figure 15 describe the control error, differential and integral errors, respectively, the last three coefficient gain schedule $k_p$, $k_i$, $k_r$.

In the second stage, the TS is fed to the SCO input, which approximates it using a user-defined fuzzy output model. The optimal representation of the linguistic variable membership functions and the number of rules is chosen.

In the second stage, the TS is fed to the SCO input, which approximates it using a user-defined fuzzy output model. The optimal representation of the membership functions of the linguistic variable is chosen. The result of the stage of construction of input linguistic variables is presented in Figure 16.

At this stage, the right parts of the rules are optimized. This uses GA, (for TS with layout) and Matlab modeling for TS obtained using model and layout.

The results of the KB construction are illustrated below (Figure 17).

For formation of the right parts of rules for KB which TS is received from a layout, GA 2 was used. The fitness function at this stage is the minimum of the TS approximation error. The result of creation and optimization of KB rules is presented in the form of a neural network in Figure 17. The first layer shows the number of input variables, the second-the number of membership functions for each variable, the third - the production rules of KB, the fourth - the values of the gain.

Figure 18 shows the relationship between the training signal obtained using a mathematical model and the gain of the fuzzy controller.

The regulators were designed to function in a typical control situation. To compare the robustness of the developed control systems, we use an unexpected control situation. The situation is modeled by the presence of noise in the coefficient of friction of the wheel on the surface and in the control action. As such noise in the experiment a special coating is used, and the corresponding parameter values were set for the models.

Consider the behavior of PID and fuzzy controllers in a typical and unexpected control situation. In Figure 19-22 the results of modeling and experiments in a typical control situation are presented.

Table 3 presents a comparison of the KB by the number of rules, the number of functions belonging to the linguistic variable and the method of optimization in the software tools of the KB.

| Knowledge base from model 1 | Number of rules | Number of fuzzy sets | Optimization method |
|-----------------------------|-----------------|----------------------|---------------------|
| Knowledge base from model 2 | 245             | 8x6x6                | simulation          |
| Knowledge base from robot 1 | 276             | 8x9x6                | simulation          |
| Knowledge base from robot 1 | 288             | 9x9x6                | Approximation of TS |
| Knowledge base from robot 1 | 270             | 5x8x8                | Approximation of TS |

Research of quality of control of the PID-regulator and fuzzy regulators on the basis of software tools of SCO was carried out with use of mathematical model and real CO. The regulators were designed to function in a typical control situation. The parameters of the mathematical model used for modeling are presented in Table 4.

Table 4. Control situations, parameters of mathematical models

| Typical situation (C1) | Unforeseen situation (C2) |
|------------------------|---------------------------|
| Initial angle          | 0р                        | 0р                       |
| Initial velocity       | 1р/с                       | 1р/с                      |
| Weight of the cart     | 0.56 кг                    | 0.56 кг                   |
| Mass of the pendulum   | 0.63 кг                    | 0.63 кг                   |
| Length of the pendulum | 0.07 м                     | 0.07 м                    |
| Friction in fastening  | 2.75 + normalized noise with intensity 0.01 and an amplitude of 0.35 | 3.55 + normalized noise with intensity 0.01 and an amplitude of 0.35 |
| Friction of the wheels | 3.63 + Gaussian noise 15%  | 2.53 + Gaussian noise 15% |
| Elastic force          | 5.54Н/м                    | 7.54Н/м                   |
| Noise in the control system | Uniform [-2.15 2.15], the intensity of 0.48 | Uniform [-2.15 2.15], the intensity of 0.48 |
| Noise in the measurement system | Gaussian noise, amplitude 0.22, intensity 0.01 | Gaussian noise, amplitude 0.42, intensity 0.01 |
| Delay on feedback control loop | 0.01 с                  | 0.01 с                    |

To compare the robustness of the developed control systems, we use an unexpected control situation. The situation is modeled by the presence of noise in the coefficient of friction of the wheel on the surface and in the control action. As such noise in the experiment a special coating is used, and the corresponding parameter values were set for the models.

In Figure 10 the structure of the modeling system is presented. Consider the behavior of PIDs and fuzzy con-
Figure 15. On the left TS from the layout (GA-PID controller), the right gain FC.

Figure 16. Membership functions for input values of linguistic variables BS1, BS2, BS3, BS4.
Figure 17. Knowledge bases in the form of neural networks (TS with model and layout)

Figure 18. TS from models and FC output gains.
trollers in a typical and unexpected control situation. In Figure 19-22 the results of modeling and experiments in a typical control situation are presented.

We will analyze the quality of control of FC and PID regulators. To do this, we use the following indicators of the transition process (Figure 23):

![Figure 19. Left error control, on the right the integral square error. Typical control situation. Modeling](image1)

![Figure 20. Left error control, on the right the integral square error. Typical control situation. Experiment](image2)

![Figure 21. Left error control, on the right the integral square error. Unforeseen control situation. Modeling](image3)
Figure 22. Control error. Unforeseen control situation. Experiment

Figure 23. Control quality indicators.

Overshoot characterizes the oscillatory property of the transition process and is calculated according to the following expression:

\[ O_1 = 1 - \frac{O_1}{O_m}; \quad O_m (\text{const}) \geq O_1; \quad (5) \]

Figure 24 shows a diagram of the level of over-regulation of control systems. A fuzzy controller developed on the basis of a verified mathematical model has a lower overshoot rate, which characterizes the operation of such a controller as more efficient.

Stability of transition process of regulators (Figure 25) is calculated as:

\[ O_2 = 1 - \frac{O_2}{O_m}; \quad O_m (\text{const.}) \geq O_2; \quad (6) \]

Figure 24. Over-regulation of control systems in a typical situation. Simulation and experiment

Figure 25. Stability of control systems in a typical situation. Simulation and experiment

The quality of control characterizes the ability of the control system to effectively consume the energy and technical resource of the system. In the case of complex control, equipment wears and energy costs will be high.

The complexity of ICS control (Figure 26) is calculated in the form:

\[ P \equiv 1 - \left( \frac{\int_0^T \left( \frac{dK}{dt} \right)^2 dt}{A (\text{const})} \right); \quad A = (\text{const}) \quad (7) \]

The evaluation of the complexity of the control showed that fuzzy controllers developed using SCO provide the system with simpler control, which ultimately has a positive effect on the life of the equipment, reducing wear and increasing reliability.
The results of the simulation and experiment in an unexpected situation are presented graphically in Figure 21-22. From the graphs (Figure 19-22) it can be seen that the PID controller does not have the necessary robustness, which in an unforeseen control situation leads to a loss of stability of the system.

Thus, the result of using the tools at the first stage of the ICS design process is the required type of universal approximator in the form of FC with an optimal KB structure (see, Figure 1, Step 1).

The technologies for remote configuration and transmission of knowledge bases allow the control object (CO) to accept the KB from the SCO block, or from other CO, which makes it possible to control structurally new objects such as robot teams, multi-agent systems, complex automated production facilities, etc. In addition, this technology allows the CO to update and adapt the KB for a specific control situation, including an abnormal situation.

5. Technology of Remote-control Object Setting

Remote control setting allows to adapt fuzzy control system to a specific (unexpected) control situation regardless of the time and location of the CO. This kind of self-organizing ICS with remote design of KB is important for elimination of consequences of accidents at the nuclear power plant, at analysis of blockages at earthquakes, train crash, for work in the polluted and radioactive environment, etc.

Let’s consider the remote connection module of the SCO and the real CO for setting up the KB. A USB connection or a Bluetooth radio channel are used for data transfer. The information is shared between the control system and the SCO to form a KB (Figure 27).

Remote KB optimization is carried out at the fourth stage of FC design. The implementation of the physical connection environment involves the use of additional equipment for receiving and transmitting data, for example, a Bluetooth radio channel, WiFi or cable connection, for example, USB.

It is assumed that the exchange of information between the control system and the SCO for the formation of KB (Figure 27). The detailed process of setting up the functioning of such a system is presented in (Figure 28).
uses the serial port. The transmission speed in this case is 115200 bps. In the process of functioning, numbers are transmitted through the COM-port in the symbolic form. Connection to the SCO is carried out through the developed plug-in (Figure 29).

Figure 29. Remote configuration module for REVIEW

The remote KB transmission is the next step in the development of the wireless connection of the CO with the SCO. In this case, it is not control actions that are transferred from the SCO, but the KBs, that is, information and knowledge of a higher level is shared. The implementation of the connection environment involves the use of the IEEE 802.11 (Wi-Fi) standard and the TCP/IP protocol for data reception-transmission. Information is shared between the control system and the SCO to form and transfer KB. Structurally, from the point of view of software engineering, the KB is implemented by a structural type of data and its size depends on the number of input and output variables, the number of membership functions of the linguistic variables and the number of production rules. At the speed of 1 Mbit/s, the transmission of a 10 KB with internal delays takes no more than 100 ms, which allows to qualitatively rebuild the ICS for a given task in the on-line mode.

As a data transmission medium consider the possibility to use the radio module presented in Figure 30 to wirelessly tune the KB of a dynamically unstable object.

Figure 30. Bluetooth radio module.

Let’s set the maximum time delay limit for receiving and transmitting data in a communication environment. The time delay is 40 MS, which is critical for typical control systems discussed earlier. Based on this, the control situation with such a delay value can be considered extreme.

To solve the control problem, we change the law of formation of the control action (1). The reference signal of the stabilization system will depend on the integral error (8), this will allow the system to function at a critical time delay:

$$\text{ref} = -a \cdot \int \text{edt} ,$$  \hspace{1cm} (8)

where a is an experimentally matched parameter equal to 0.25. In expression (8), the angle of the reference signal depends on the accumulated integral error. It is important to note that in addition to the value of the setting signal was imposed restriction, and its value should not go beyond the aisles of the range [-16, 16].

The result of the TS approximation is the constructed KB for FC, including an optimal finite set of rules and optimally generated parameters of the membership function of the input and output variables of the FC. Thus, the result of designing is a required type of the universal approximator in the form of FC with an optimal structure of the KB.

Let’s compare the PID controller (PID) with the FC (FC1), optimized with the help of the remote setting to control object. Figure 31 (a) represents the angle of deviation of the controllers being compared, and Figure 31 (b) shows an integral estimation of the deviation angle in a typical situation. Figure 32 (a) shows the level of the left and right wheel departure from the launch point, and Figure 32 (b) represents an integral assessment of departure.

Figures 31 and 32 show that the FC error level is below the PID controller, both in terms of the deviation angle and the departure from the launch point.

Practice and simulation results have shown that in conditions of uncertainty or inaccuracy of initial information, unforeseen situations or information risk, the traditional (using the principle of global negative feedback) and widely used in the industry PID regulator often fails to cope with the task of control. At the same time, the solution of the problem of global robustness of the PID controller is still unknown, despite the relevance of this problem.

The use of fuzzy controllers (FC) in conjunction with the PID controller led to the creation of hybrid fuzzy issues with different levels of intelligence depending on the completeness and correctness of the designed knowledge base.
The use of soft computing technology (based on genetic algorithms and fuzzy neural networks) has expanded the effective application of FC by adding new functions in the form of learning and adaptation. However, in the general case of abnormal control situations, it is very difficult to design a globally "good" and robust ICS structure. This limitation is especially typical for unforeseen control situations when the CO operates in sharply changing conditions (sensor failure or noise in the measuring system, the presence of a delay time of control or measurement signals, a sharp change in the structure of the CO or its parameters, etc.). The solution of such problems can be found on the basis of the introduction of the principle of self-organization of KB in the design process of FC, which is implemented and programmatically supported by the developed model of QFI using the methodology of quantum soft computing and system engineering-System of System Engineering (synergetic principle of self-organization) \(^\text{[20]}\).

Figure 31. The deviation angle of an inverted pendulum (a), the integral estimation of the deviation angle (b)

Figure 32. The departure of the right and left wheels from a start point (a), integrated assessment of departure from the start point

The proposed model uses private QFI individual KB FC, each of which is obtained with the help of the knowledge base optimizer (SCO) for the corresponding conditions of operation of the OC and fixed control situations in an external random environment. The process of designing private individual KB FC using software tools SCO for given control situations is carried out in accordance with the design technology and is discussed in detail in \(^\text{[23]}\).

6. Structure and Basic Functions of Quantum Fuzzy Inference

The purpose of applying quantum computing and creating a self-organizing quantum controller is to combine the intelligent controllers of various sensors obtained in the first stage into a self-organizing connected multi-agent network based on a quantum controller and cognitive-informational interaction between knowledge (KB) (Figure 1, Step 2). Structural implementation of the process of self-organization in the QFI model \(^\text{[19]}\) presented in Figure 33.

The basic idea is to find the possibility to use the classical states of various regulators (sliding, fuzzy, classical) for achieving goal of control in unforeseen situation. Quantum fuzzy inference (QFI) technology ensures the required level of robustness, without changing the lower
level of control, only through the use of software level.

Figure 33. Structural implementation of the process of self-organization in the QFI model:

In this case, the robustness property (by its physical nature) is an integral part of self-organization, and the required level of robustness of the ICS is achieved by fulfilling the principle of minimum production of generalized entropy noted above. The principle of minimum entropy production in the CO and control system serves as the physical principle of optimal functioning with a minimum consumption of useful work and is the basis for the development of a robust ICS.

Reliable functioning of natural self-organizing systems is provided by using their individual properties, a combination of these approaches and algorithmic formation of a complex of properties in changing or unforeseen conditions. The process of designing robust KB corresponds to the abovementioned process of optimal support of the introduced thermodynamic relationship between the noted fundamental qualities of control (thermodynamics control quality trade-off, obtained as a physical criterion of self-organization).

Let us emphasize that the effect of self-organization of KB in the ICS is based on the virtual process of extracting additional (hidden) quantum information from the reaction (to an unforeseen situation) of classical control signals at the output of KB, designed in the learning environment, and is physically implemented by software tools based on QFI.

In Figure 34 (as the realization of the structure in Figure 33) the functional structure of the simplified QFI model is shown.

Figure 34. The functional structure of a QFI in real time

The following steps are implemented in the SC model for QFI:

1) the fuzzy output results of each independent individual FC are processed;
2) choose the type of quantum correlation;
3) a superposition is formed for the selected quantum correlation;
4) the valuable quantum information hidden in independent individual KB is extracted (on the principle of minimum entropy in the extracted quantum knowledge – maximum amplitude of probabilities of "intelligent state") on the basis of methods of the quantum theory of information;
5) in real time, a generalized output robust control signal is projected on a set of KB in the form of FC reactions to a new control error.

QFI was realized with the help of software tools – quantum optimizer (QSCOptKB™). QFI itself is a new quantum search algorithm that realizes the search in dissimilar spaces of solutions embedded in KB. QFI, as a special case of the quantum algorithm, includes superposition and quantum oracle operators. In addition, which makes the algorithm unique, are used quantum correlations matrix as a source of additional information latent in classical information states, (tensor multiplication with the extraction of additional hidden information embedded in classical signal states.

In this case, the output signal of the QFI in real time represents the optimal control signal for changing the gain coefficients of the fuzzy PID controller in the ICS of a specific robot control task. The signal includes the necessary (best) quality characteristics of the control output signals of each FC, thus realizing the principle of self-organization. Qualitative features of the synergistic effect of self-organization are taken into account in the selected type and type of quantum correlation.
At the physical level of interaction of robotic systems, the effect of self-organization introduced in accordance with the information-thermodynamic criteria, provides the system with a minimum loss of useful resource even in unforeseen control situations, such as the delay of the control action. At the same time, the minimum of initial information about the system, without destroying the lower executive level of the system control and without adding additional sensors, allows for the solution of new control problems manifested in the interaction of groups of robots.

Consider the possibilities of the organization Synergetic Effects of Information-Cognitive Interaction in Intelligent Socio-Cyber-Physical Robotic Systems with Remote Knowledge Exchange for starters. Using the classic control theory problem as an "cart – pole system (inverted pendulum)" as an example, consider the design process of an intelligent robust control system using soft and quantum computing.

The main task solved by the QFI is the formation of KB with an increased level of robustness from a finite set of KB for FC, formed with the use of soft computing technology. Let us briefly consider the functional structure and operation of the main blocks of QFI. As an example, without losing the generality of the result, we will discuss the processes of extraction of hidden quantum information, data processing and the formation of robust KB FC, using the KB of two FC, designed for fixed (different from each other) control situations.

Using a standard decoding procedure (the internal product of vectors in Hilbert space) and selecting scaling coefficients for the output values of the projected gain (Figure 34, block 6), the iterative work of the SC QFI is carried out. The possibility of remote connection of the CO to a stationary computer system opens the possibility of remote configuration, formation and self-organization of BP FC in online.

7. Quantum Computing on a Classical Processor: Application in Robust Control of an Unstable CO

Designing a control system based on QFI is carried out using the developed software tools "Quantum optimizer" [19]. The technology of application of QFI allows to unite in uniform control system of several KB, and thus, allowing fuzzy neural networks to work in parallel (Figure 35).

Let us consider the possibility of using QFI to combine the KB obtained on the basis of a training signal from a physical object (GA-PID controller) and a verified mathematical model (Figure 36). Before proceeding to the creation of quantum FC, it is necessary to obtain histograms of the distribution of the output signals (gain) of fuzzy controllers (Figure 36).

![Figure 35. Intelligent control system of inverted pendulum, manipulator and mobile platform with QFI](https://doi.org/10.30564/aia.v3i2.3849)

![Figure 36. Histograms of output values of fuzzy controllers](https://doi.org/10.30564/aia.v3i2.3849)
equipment for receiving and transmitting data, for example, a Bluetooth radio channel, WiFi or cable connection, for example, USB. The exchange of information between the CO and the quantum optimizer (QO) is assumed to search for scaling coefficients (block 6, Figure 34) the quantum of the regulator. As a result of the design, the output signal from the QFI unit is used to control the gain of the PID controller in the case of modeling a mathematical model, and for a robot in a physical experiment, an exported file with the extension "* " is used. after.»

8. The Results of Simulation and Experiment in Unforeseen Control Situation

We consider the application of the developed model of QFI for the formation of control processes of gain fuzzy PID controller. To do this, we will conduct a computer simulation for two control situations:

- in the first (typical) situation (C1) the delay of the control signal is standard-0.01 sec;
- in the second Unforeseen (C 2), the control signal delay is 0.04 sec (quadrupled).

Table 5 presents the parameters of the mathematical model for C1 and C2.

| Table 5. Control situations and parameters of mathematical models |
|---------------------------------------------------------------|
| **Typical situation (C1)** | **Unforeseen situation (C2)** |
| Initial angle | 0dg | 0dg |
| Initial velocity | 1dg/c | 1dg/c |
| Weight of the cart | 0.56 kg | 0.56 kg |
| Mass of the pendulum | 0.63 kg | 0.63 kg |
| Length of the pendulum | 0.05 m | 0.07 m |
| Friction in fastening | 3.55 + normalized noise with intensity 0.01 and amplitude 0.35 |
| Friction of the wheels | 3.63 + Gaussian noise, Amplitude 15% |
| Elastic force | 5.54H/m |
| Noise in the control system | Uniform noise [-2.15, 2.15], intensity 0.48 |
| Noise in the measurement system | Gaussian noise, Amplitude 0.22, intensity 0.01 |
| Delay on feedback control loop | 0.01 c |

In Figure 37 the structure of the modeling system is presented:

The results of modeling regulators in a typical control situation are illustrated in Figures 38 and 39.
Consider the relationship between input and output QFI values on the example of proportional gain. Figure 40 presents the input values of QFI and the output value of the proportional coefficient of QFI spatial correlation.

![Figure 40. The gain $K_p$. The input and output values of QFI. Modeling in a typical control situation](image1)

In Figure 41 results of the angle of deviation (the case of the mathematical model) in unforeseen control situation demonstrated.

![Figure 41. The angle of deviation of the mathematical model. Unforeseen control situation. Modeling](image2)

In Figure 42 the general diagram of the integral of square error of modeling is presented.

![Figure 42. Integral of square error. Unforeseen and typical control situations. Modeling. FC1-FC4-fuzzy regulators, abbreviations Q-quantum, S (Space) - spatial, T(Time) – temporal, ST(Space-Time) – spatial-temporal correlations](image3)

Note that in Figure 42 the value of the integral error of the quantum fuzzy controller is located between the corresponding graphs of the controllers that formed the QFI.

Consider the results of the experiment in a typical control situation. For Figs 43-45 the results of experiments in a typical control situation are presented.

![Figure 43. The angle of deviation of the layout. Typical control situation. Experiment](image4)

![Figure 44. The angle of deviation of the layout. Typical control situation. Experiment](image5)

![Figure 45. Integral of square error. Typical control situation. Experiment](image6)
Consider the results of an experiment in an unexpected control situation (C 2). In Figure 46-48 the results of experiments in an unexpected control situation are presented.

The control evaluation showed that FC developed with the use of SCO provide the system with simpler control, which ultimately has a positive effect on the life of the equipment, reducing wear and power consumption. The developed methodology of combining control strategies allows to effectively cope with control tasks even in unforeseen situations, in which the task of control can't cope with the FC underlying the QFI. Thus, we have a new synergistic effect due to the quantum self-organization of knowledge: the intelligent controller designed on the basis of QFI copes with the task of control and has a robust KB, which is based on non-robust KB (see, Figures 43 and 44). At the same time, the QFI-based control system inherits the best control quality characteristics from the KB of previously designed fuzzy controllers, adding the ability to self-organize in on line.

Consider the behavior of PID and fuzzy controllers in an unforeseen control situation. Figure 49 presents the results of modeling and experiments in a unforeseen control situation.

The experiment compares the different types of control, such as PID controller, Fuzzy controller, the Quantum controller. In unforeseen control situation, the classical PID and fuzzy controllers did not cope with the control task. One can see the limitations of the possibilities of the classical regulator. Also, modeling showed limitations of the use of a fuzzy controller.

In the Figure 49, a new synergistic effect of imperfect knowledge self-organization demonstrated. Individual regulators fail to task of control in unforeseen situation, but their joint using in a system with a quantum inference cope with the control goal task, and control output occurs in on line, without delays. And Figure 49 shows the unstable response of two fuzzy controllers and the stable response (of created from these fuzzy controllers) quantum controller to an unforeseen situation.

Technologies for remote configuration and transmission of knowledge bases allow the control object to receive knowledge bases from the optimizer block or from other control objects, which allows to control structurally new objects such as robot groups, multi-agent systems, complex automated production complexes. In addition, this technology allows the control object to update and adapt the knowledge base for a specific control situation using a real control object.

In the multi-agent system, there is a new synergetic information effect of self-organization of knowledge bases and formation of an additional information resource that arises in the exchange of information and knowledge between active agents (swarm synergetic information effect).

9. Modeling and an Interaction Experiment of a Group of Robots

The prototypes of a manipulator, an inverted pendulum and a mobile manipulator, act as mutual CO. The mobile manipulator equipped with an image recognition system based on the computer vision library OpenCV and such hardware as a Web camera, Kinect console and an infrared sensor. The decentralized and hierarchical variants of interaction of a group of robots are considered. An experi-

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Figure 46. The angle of deviation of the layout. Unforeseen control situation. Experiment

Figure 47. The angle of deviation of the layout. Unforeseen control situation. Experiment

Figure 48. Integral of square error. Typical control situation. Experiment
Figure 49. Unforeseen control situation

This interaction implements the hierarchical control in the master – slave combination. Thus, the inverted pendulum acts as a slave and executes commands from the mobile manipulator that has an additional sensor to determine the position of the pendulum. Such interaction is standard and possible to apply in a wide range of tasks. In addition to the obvious possibilities of automation of the cafes and bars, it is also possible to automate many production tasks, such as loading and unloading containers, sorting, etc.

The embedded level of computational intelligence in intelligent control systems of an inverted pendulum, a mobile trolley and a manipulator makes it possible to increase the robustness of the complex interaction of several robotic systems and ensure the achievement of the control goal with a high level of reliability.

Example: Quantum intelligent control of robotic manipulator. For completeness of material presentation adding that in the case of interaction of a group of robots, ICS were developed for each system separately. For example, using QFI allowed to manipulator:

- solving the problem of positioning in regular situations;
• improving the results of the positioning task in conditions of external unforeseen situations (under internal unforeseen situations the results do not change at best);
• increase in the criterion Performance by 5 times;
• improving the assessment of general management, the best result is achieved by using spatial correlation of all seven FC’s.

Figure 51 shows results simulation of manipulator control.

Figure 50. Mobile manipulator performs gripping of the glass with an inverted pendulum

Figure 51. The movement of manipulator in a standard control situation: under control of ICS based on SCO with soft computing (left); ICS based on SCO with quantum computing (right)

It should be noted that increasing the level of accuracy (more than $10^4$ times) of manipulator control is a key factor to improve the reliability of achieving the goal of
quantum intelligent control in a complex task with the cognitive interaction of a group of robots. So, the operation of capturing the glass, which in turn is a dynamically unstable object, requires the control system to develop such a control action that would compensate for the inaccuracy of the pendulum and the mobile cart.

10. Conclusions

The information technology of knowledge base remote design and transmission of the smart fuzzy controllers with the application of the "Soft / quantum computing optimizer" software toolkit developed.

The physical realization of SW/HW applications of the transmission and communication system between robots using remote connection the knowledge bases to the intelligent controllers considered.

A comparison of the control quality between fuzzy controllers and quantum fuzzy controller in various control modes demonstrate the quantum supremacy of quantum fuzzy controller.

Analysis of the experiments shows the possibility of the ensured achievement of the control goal of a group of robots using soft / quantum computing technologies in the design of knowledge bases of smart fuzzy controllers in quantum intelligent control systems.

The ability to connect and work with a physical model of control object without using than mathematical model demonstrated.

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EDITORIAL

Learning in AI Processor

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AI processor, which can run artificial intelligence algorithms, is a state-of-the-art accelerator, in essence, to perform special algorithm in various applications. In particular, these are four AI applications: VR/AR smart phone games, high-performance computing, Advanced Driver Assistance Systems and IoT. Deep learning using convolutional neural networks (CNNs) involves embedding intelligence into applications to perform tasks and has achieved unprecedented accuracy [1]. Usually, the powerful multi-core processors and the on-chip tensor processing accelerator unit are prominent hardware features of deep learning AI processor. After data is collected by sensors, tools such as image processing technique, voice recognition and autonomous drone navigation, are adopted to pre-process and analyze data. In recent years, plenty of technologies associating with deep learning AI processor including cognitive spectrum sensing, computer vision and semantic reasoning become a focus in current research.

According to different applications, deep learning AI processor can be divided into a high performance processor for neural network deployed in a cloud computing center and a low-power processing unit deployed in a mobile platform.

In recent years, almost all research departments of technology companies around the world such as IBM, Intel, and NVIDIA are dedicated to the study of the AI processors. Many scholars proposed various novel AI processor architectures, which can satisfy their companies’ demands for different applications. Eyeriss is a spatial architecture for energy-efficient dataflow for convolutional neural networks and minimizes data movement energy consumption, proposed by Yu-Hsin Chen from MIT. Eyeriss is realized by exploiting local data reuse of filter weights and feature map pixels, i.e., activations, in the high-dimensional convolutions, and minimizing data movement of partial sum accumulations [2]. ShiDianNao is a shifting vision processor and designed by Zidong Du, a professor of Chinese Academy of Sciences. It is 60× more energy efficient than the previous state-of-the-art neural network accelerator, placed next to a CMOS or CCD sensor. Zidong Du and his team present a full design down to the layout at 65 nm, with a modest footprint of 4.86 mm² and consuming only 320mW, but still about 30× faster than...
high-end GPUs \[^3\].

The artificial intelligence research still has a big gap with living things intelligence, especially in processor and smart chip, although many fields have got great achievements last several decades. Fully utilize AI processor research to benefit all sectors of industry. The challenges confronting AI processor are profound and there is still extensive research work to carry out. Therefore, the author lists three promising AI processor technologies for discussion.

Most AI processors are suitable for task in a specific application, like autonomous driving of drones and cars. A general and powerful architecture of AI processors will emerge to eliminate the customization hardware work.

Accompanied by the sharp increase in computation of signal processing, multi-core interconnection and real-time and low-power will be the hard parts of AI processor, when a heterogeneous multi-core architecture SoC is designed \[^4\].

Another problem of CNN is categorization, both in image and semantic. While the solution to bridge the gap remains elusive, there are many promising algorithms to propose toward this goal \[^5\].

Finally, as editorial board members, we would like to thank the authors for their submissions. By compiling these articles, we hope to enrich our readers and researchers with recent trends. Certainly, all AI topics could be accepted to publish on this journal.

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