SO-MRS: a multi-robot system architecture based on the SOA paradigm and ontology

Kamil Skarzynski\textsuperscript{1}, Marcin Stepniak\textsuperscript{1}, Waldemar Bartyna\textsuperscript{1}, and Stanislaw Ambroszkiewicz\textsuperscript{2},

Abstract—A generic architecture for a class of distributed robotic systems is presented. The architecture supports openness and heterogeneity, i.e. heterogeneous components may be joined and removed from the systems without affecting its basic functionality. The architecture is based on the paradigm of Service Oriented Architecture (SOA), and a generic representation (ontology) of the environment. A device (e.g. robot) is seen as a collection of its capabilities exposed as services. Generic protocols for publishing, discovering, arranging services are proposed for creating composite services that can accomplish complex tasks in an automatic way. Also generic protocols for execution of composite services are proposed along with simple protocols for monitoring the executions, and for recovery from failures. A software platform built on a multi-robot system (according to the proposed architecture) is a multi-agent system.

I. INTRODUCTION

The general assumption is that multi-robot system (MRS for short) consists of an environment, and of devices that operate in the environment and may change its state. A device may be considered as an element of the environment, and the device state may be subject of change, e.g. its position. The crucial questions, for a MRS to be designed and developed, are: What is the purpose of the system? What kind of problems is it supposed to solve, or what class of tasks are to be accomplished in the system? If the system is dedicated to a fixed class of tasks, then the tasks as well as the methods for the task accomplishing may be hard-coded during the design process.

In the paper, a special kind of MRS is considered. It is supposed that the devices may be heterogeneous, and can be added to the system as well as be removed without affecting its basic functionality, i.e. the generic ability for task accomplishing. Hence, the class of the tasks is not fixed and depends on the joint capabilities of the devices currently available in the system. Since such tasks can not be hard-coded in the system, there must be a language for the task specification. Intuitively, a task is an intention to change local state of the environment. That is, task consists of precondition and effect. Sometimes the precondition is not necessary. Precondition specifies initial local state of the environment, whereas the effect specifies the desired environment state after the task performance. So that, a formal representation of the environment (ontology) is needed. It is also supposed that the devices are not isolated, i.e. there is a minimum communication in the system in the form of (wireless) network. That is, each device has a network address and can receive and send messages.

Each device is autonomous and may provide some services (via its Service Manager) for a client (i.e. human user or software application). If a client has a task to be accomplished, it sends a request to the device. Then, the service may accomplish the task, if it has enough resources and capabilities. Hence, each device provides some services that correspond to some types of elementary tasks the device may accomplish. The formal specification (expressed in a language of the common ontology, e.g. OWL-S [1]) of the type of a service consists of a precondition and an effect. The service type must be published by a device (to be joined to MRS) to a Registry. Client may discover the service, and invoke it. This constitutes the essence of the Service Oriented Architecture (SOA) paradigm [2] in Information Technology. Repository (the next component of MRS) is a realization of the common knowledge of the environment representation (ontology), and a storage of the current maps of the environment, i.e. instances of the ontology. Since the environment may be changed by devices, the maps must be updated.

If a client wants to realize a complex task (a sequence or partial order of the elementary tasks), then some services, that may jointly accomplish the complex task, should be composed into a workflow (composite service). An additional component of MRS is needed for doing so. It is called Task Manager, and it is responsible for constructing an abstract plan in the form of partial order of service types. Then, appropriate services should be arranged. Finally, the workflow is executed and its performance is monitored. If a failure occurs (due to a broken communication or inability of a service to fulfill the arranged commitment), then failure recovery mechanisms must be applied. Simple mechanisms (in the form of protocols) consist in re-planning, and changing some parts of the workflow in order to continue the task execution.

To summarize, the software infrastructure (actually, a multi-agent system) built on MRS (for complex task accomplishing) consists of services exposed by Service Managers on devices (robots), service Registry, Task Manager, and Repository. The interactions between them are based on generic protocols for publishing, discovering, composing elementary services, arranging, execution, monitoring and recovery from failures. Note that the basis for the protocols is a formal representation of the environment (ontology) that allows to specify local states of the environment, tasks, service

\textsuperscript{1} Waldemar Bartyna  (wbartyna@gmail.com), Kamil Skarzynski  (kamil.skar@gmail.com), and Marcin Stepniak  (martinus.st@gmail.com) – Institute of Computer Science, University of Natural Sciences and Humanities, Siedlce, Poland

\textsuperscript{2} Stanislaw Ambroszkiewicz – Institute of Computer Science, Polish Academy of Sciences, Jana Kazimierza 5, 01-248 Warsaw, Poland, sambrosz@ipipan.waw.pl
types, intentions, commitments, and situations resulting from failures. Roughly, this constitutes the proposed architecture called Service Oriented Multi-Robot System (SO-MRS for short).

SO-MRS architecture follows the hybrid approach based on additional infrastructure where main components of the infrastructure may be multiplied, i.e. in one MRS, there may be several independent Task Managers, Registries, and Repositories. Note that the presented approach is at higher level of abstraction than Robot Operating System (ROS) that is usually used to implement services on the devices. The main contribution consists of simple universal upper ontology, MRS architecture, and generic protocols.

The presented work is a continuation of Ambroszkiewicz et al. (2010) [3].

II. MOTIVATIONS AND RELATED WORK

Rapid development and ubiquitous use of intelligent devices (equipped with sensors, micro-controllers, and connected to a network) pose new possibilities and challenges in Robotics and Information Technology. One of them is creating large open distributed systems consisting of heterogeneous devices that can inter-operate in order to accomplish complex tasks. Ambient Intelligence (AmI), and Ubiquitous robotics are currently extensively explored research areas. It is supposed that in the near future humans will live in a world where all devices are fully networked, so that any desired service can be provided at any place at any time. It is worth to notice the Intelligent Physical Systems research program by NSF, and Machine-to-Machine (M2M) standards promoted by International Telecommunication Union [http://www.onem2m.org/]. AmI and Ubiquitous robotics require new information technologies for developing distributed systems that allow defining tasks in a declarative way by human users, and an automatic task accomplishing by the system. Openness and heterogeneity of the systems are essential because of the scalability, see Di Ciccio et al. (2011) [4], and Helal et al. (2005) [5].

A lot of work has been done starting with the seminal papers by Fukuda et al. 1987 [6], and by Asama et al. 1989 ACTRESS [7]. Several architectures were proposed for multi-robot cooperation: a pure swarm robotics approach using large numbers of homogeneous robots, e.g. Mataric (1995) [8], and Cao et al. (1997) [9], a behavior-based approach without explicit coordination, e.g. ALLIANCE Parker (1998) [10], and a hybrid approaches, e.g. Distributed Robot Architecture (DIRA) Simons et al. (2001) [11]. DIRA is closely related to SO-MRS, however, it was not fully developed. For a comprehensive overview, see Parker (2008) [12].

Actually, the proposed SO-MRS architecture follows the idea of ASyMTRe-D and IQ-ASyMTRe [13] [14] [15]. However, instead of sharing (by devices) mutually data from their sensors, SO-MRS is equipped with explicit common ontology as the basis for constructing generic protocols.

There are some other approaches that apply SOA paradigm, Semantic Web and Web Services technologies to multi-robot systems, like the Ubiquitous Robotic Service Framework (URSF) project (2005) [16] and (2007) [17], Aiello et al. (2008) [18], and Kaldeli et al. (2013) [19]. The project Service Oriented Device Architecture SODA Alliance [20], and its extension in the form of OASIS standard Devices Profile for Web Services (DPWS) [21], is also of interest. Device functionality is described there in the very similar way as it is done for Web services. For an extensive overview of SOA based robotic systems (from software engineering point of view) see de Oliveira (2015) [22]. Although these approaches are also based on SOA, what makes the difference (in comparison to SO-MRS) is the lack of ontology, i.e. a common representation of the environment, and the language describing the representation. This very ontology is the necessary basis for constructing the generic protocols for automatic complex task execution and for recovery from failures.

It is worth to notice that the following view presented by Parker (2003) [23] is still up to date: “A general research question in this vein is whether specialized architectures for each type of robot team and/or application domain are needed, or whether a more general architecture can be developed that can easily be tailored to fit a wider range of multi-robot systems.”

It seems that there are still a lot of problems to be solved in the domain of multi-robot systems. Recent research directions are focused rather on software level. The player/stage project, Gerkey et al. (2003) [24] developed software level approach whereas the more abstract software independent level is needed. An abstract (however still unsatisfactory) approach was proposed by Kramer and Magee (2007) [25] as the software engineering point of view of the problem. The idea of Jung and Zelinsky (2000) [26], and Hugues (2000) [27] of common grounded symbolic communication between heterogeneous cooperating robots is very close to the concept of common ontology, however, it was not fully developed and not continued. An interesting approach to composite services (heterogeneous robot teams) as temporal organizations with elements of recovery from failures was presented in Zhong and DeLoach (2011) [28].

Let us also cite the view on the research on MRS by Chitic, Ponage and Simonin (2014) [29]: “Despite many years of work in robotics, there is still a lack of established software architecture and middleware, in particular for large scale multi-robots systems. Many research teams are still writing specific hardware orientated software that is very tied to a robot. This vision makes sharing modules or extending existing code difficult. A robotic middleware should be designed to abstract the low-level hardware architecture, facilitate communication and integration of new software.”

III. ENVIRONMENT REPRESENTATION

Classic representations of robotic environments (see Thrun et al. (2002) [30] for a comprehensive overview) are based on metric and topological approaches dedicated mostly to tasks related to navigation. Another approach, Spatial Semantic Hierarchy (SSH), Kuipers (2000) [31], is based on the
consists of the following concepts: In its general form it is an upper ontology, and protocols (presented roughly below) to accomplish complex details), and sufficient together with simple and universal is simple, it is generic (abstracting from implementation is needed for MRS.

In the Computer Science related to Robotics, the term “ontology” is equivalent to the “general structure of the representation of a multirobot system environment”. The most popular definition of ontology was given by Tom Gruber (1993) [38] in the following way: ontology is a specification of a conceptualization. Conceptualization is understood here as an abstract and simplified model (representation) of the real environment. It is a formal description of concepts (objects) and relations between them. Since the model is supposed to serve the interoperability, it must be common and formally specified, i.e. the definitions of objects and relations must be unambiguous in order to be processed automatically.

Two recent standards developed by groups of the IEEE RAS and addressing robot ontologies and map representation [https://standards.ieee.org/findstds/standard/1872-2015.html](https://standards.ieee.org/findstds/standard/1872-2015.html) [https://standards.ieee.org/findstds/standard/1873-2015.html] are closely related to upper ontology presented below. However, these ontologies are complex and include specifications even for defining processes for task execution. Our ontology is extremely simple, and is at the higher level of abstraction, i.e. it abstracts from recognition of physical objects, and is focusing only on generic attributes of the objects that can be measured, recognized or evaluated. Although the proposed ontology is simple, it is generic (abstracting from implementation details), and sufficient together with simple and universal protocols (presented roughly below) to accomplish complex tasks in open and distributed heterogeneous multi-robot systems. In its general form it is an upper ontology, and consists of the following concepts:

- attributes that define properties of object (e.g.: color, weight, volume, position, rotation, shape, texture, etc.,
- relations that express dependencies between objects,
- types of objects that specify object attributes, constraints on attribute values, and relations between sub-objects,
- object that is an instance of a type with concrete attribute values, sub-objects and relations between them.

In order to add a new type to the ontology one has to specify:

- parent type, i.e. the type that the new type inherits from,
- list of attributes of the new type,
- list of types of obligatory sub-objects, i.e. types of objects that are integral parts of the type being defined, e.g. legs in the case of the type of table,
- list of constraints specifying attribute values as ranges and/or enumerations, and obligatory relations between sub-objects.

The type inheritance provides hierarchical structure supporting management of existing types as well as creation of new types. In the presented ontology the most generic type called Object is inherited by two types: PhysicalObject and AbstractObject as shown in Fig 1. The types are for separating physical objects that are directly recognizable by robots from abstract objects that are hierarchically composed from physical objects, relations between them, and attributes.

Descendants of PhysicalObject type, that are leaves in the inheritance hierarchy tree, are called elementary types. They are described only by attributes (simple and/or complex attributes) that can be recognized by robots. The type CuboidFurnitureLeg is an example of an elementary type. It is defined by the following attributes: PositionX, PositionY, PositionZ, RotationX, RotationY, RotationZ, Shape, Weight, Texture, and the constraint: Shape is CuboidFurnitureLegShape. Shape is a complex attribute consisting of its own attributes and their constraints. The constrains are important for object recognition, e.g. attribute constrains of the FurnitureLeg type are different than the constrains of the type corresponding to building pillars.

The AbstractObject branch consists of complex abstract types. Each such type is defined as a collection of types (complex and/or elementary), and relations between objects of these types. The type CuboidRoom is an example of an abstract type. Internal structure of an object of this abstract

![Fig. 1. Main object types](https://standards.ieee.org/findstds/standard/1872-2015.html)
type is composed of elementary objects such as walls, floor, ceiling, windows, and doors, as well as the relations between these objects.

General structure of the proposed representation of the environment is defined as a hierarchy of types. Elementary type is defined as a collection of attributes with restricted ranges, whereas an abstract type is defined by some of the previously defined types (abstract and/or elementary), and relations between objects of these types. The type Building consists of several other abstract types like storey, passages, rooms, stairs, lifts, etc.

The attributes and relations are the basic elements for creating representation, i.e., construction of object types. A particular object (an instance of its type) is defined by specifying concrete values of its attributes, specifying its subobjects (if it is of abstract type) and relations between them. Instance of the general structure (called also a map of the environment) is defined as a specification of an object of an abstract type, for example, of the type Building. In order to support an automatic map creating and updating (by mobile robots), the attributes must be recognizable and measurable by robot sensors.

IV. Services
There are three kinds of services:
- Physical services that may change situations in the physical environment.
- Cognitive services that can recognize situations described by formulas of the language of the ontology.
- Software services that process data.

A service interface consists of the following elements:
- Name of the type of service, i.e. name of an action that the service performs.
- Specification of the inputs and outputs of the service.
- The condition required for service invocation (precondition), and the effect of service invocation.
- Service attributes as information about the static features of a service, e.g., operation range, cost, and average realization time.

Precondition and effect are defined as formulas of a formal language (OWL [39], or Entish [40]) describing local situations in the environment. Entish is a simplified version (without quantifiers) of the first order logic. It has logical operators (and, or), names of relations (e.g., isIn, isAdjacentTo), names of functions (e.g., action, range), and variables. A precondition formula is a description of the initial situation, and the effect formula is a description of the final situation.

V. SO-MRS Architecture
Figure 2 shows the proposed architecture of multi-robot systems designed according to the SOA paradigm [41]. The system components communicate with each other by using generic protocols. Repository stores ontology, and provides access to object maps for the other system components. It has also a graphical user interface (GUI) for developing the ontology, and for its management.

Task Manager (TM for short) represents a client, and provides a GUI for the client to define tasks, and to monitor their realization. The Planner provides abstract plans for TM, that are used to construct a concrete plan (workflow) on the basis of information on available services (provided by Service Registry). The workflow is constructed by arranging concrete services. Arrangement is performed by TM (via the

Arrangement Module) by sending requests to services (in the form of intentions), and collecting answers as quotes (commitments). TM controls the plan realization by communicating with the arranged services.

Service Registry stores information about services currently available in the system. Each service, in order to be available, must be registered to Service Registry via Service Manager (SM) that is a robot (device) interface for providing its services for an external client. In this case, TM acts as a client. SM controls the execution of subtasks delegated by TM, and reports the success or failures to TM.

Task is defined (on the basis of the ontology stored in Repository) as a logical formula that describes the initial situation (optionally) and the required final situation in the environment. For a given task, Planner returns abstract plans that, when arranged and executed, may realize the final situation specified by the task in question. An abstract plan is represented as a directed acyclic graph where nodes are service types and edges correspond to causal relationships between the output of one service and the input of another service. The relationship determines the order of arrangement, and then also the order of execution of a concrete plan (workflow) called also a business process. A concrete plan may also include handlers responsible for compensations, and failure handling to be explained below.

VI. Protocol for Failure Handling and Recovery
Since some ideas and methods are adopted from electronic business transactions, realization of a task is called a transaction. All services are invoked within a transaction that contains a dynamic set of participants. The transaction is successfully completed, if the delegated task is accomplished.
Special transaction mechanism designed for handling failures has the following properties.

1) Failed services may be replaced by other services during task realization.
2) The general plan may be changed.
3) The transaction ends either after successful completion of the task, or inability to complete the task, or cancellation of the task.

The classic meaning of the term transaction in Information Technology goes back to the ACID properties of modifying a database. Long-running transactions avoid locks on non-local resources, use compensations to handle failures, potentially aggregate smaller ACID transactions (also referred to as atomic transactions), and use a coordinator to complete or abort the transaction. In contrast to rollback in ACID transactions, a compensation restores the original state or an equivalent one, and it is domain-specific, e.g. for a failure when transporting a cargo by one robot, a compensation may be done by arranging another robot that can continue the transport to the destination, and charging (as a penalty) the owner of the first robot for the delay.

SO-MRS architecture was implemented twice. The first implementation was done within the framework of Robo-enT project (2005-2008) with mobile robots Pioneer 3 (P3-DX).

The Autero system (the RobREx project (2012-2015)) is the second implementation of revised and extended SO-MRS architecture with new version of the ontology and new protocols; see [http://www.robrex.ipipan.eu/about.php?lang=en](http://www.robrex.ipipan.eu/about.php?lang=en) for the experiments. The system has been tested in a universal simulation environment implemented in Unity 3D. The class of tasks that can be accomplished in a real environment is always limited by the number and capabilities of available devices (robots). From the point of view of the proposed information technology (the architecture, ontology and protocols), the fact that the test environment is simulated is irrelevant. The simulation environment is generated automatically (!) from the contents of Repository. Service Managers are implemented as independent components that communicate with robots in the simulation environment via TCP/IP protocol.
Fig. 4. “Moving a jar” scenario

Scenario 1 - moving a jar from a cupboard to a platform:
The task was realized by a single TransferObject service on
a mobile robot with a gripper. The task is defined as:

- precondition: Jar002 isOn ?Shelf
- effect: Jar002 isOn Platform001

In the arrangement phase, precondition and effect of the task
are sent in an Arrange message to the Service Managers
that can provide the TransferObject service. Two services
of this type are registered in the system, so that, two
Service Managers (representing these services) receive the
same query. Service Managers respond with Terms messages,
each of them contains a commitment. Additional service
attributes (maximum service execution time, and price) are
also specified. Service 2 has a shorter execution time whereas
service 1 requests much lower payment. So that, service 1
is selected for the task. The SM of service 1 is notified by
an Accept message, whereas the SM of service 2 receives a
Cancel message. The precondition is sent within an Execute
message initializing execution phase. After receiving this
message, the Service Manager starts the task execution by
moving the robot closer to the cabinet so that the object to be
transported is within the range of the robot gripper. Then, the
object is grabbed, the gripper is set to the transport position,
and the robot approaches the platform on which the jar is put
down. Then, SM sends a Completed message containing the
description of the resulting situation. In this scenario, one
service is needed for the task, so that, after the successful
service execution, the task is considered as completed and
transaction can be ended. The Task Manager does this by
sending an End message to the Service Manager.

Scenario 1b - failure: Failures might occur during the
transportation, e.g. the robot drive was out of order. In
such a situation, the robot has a control unit that can
communicate with other system components. It also has an
active gripper. Hence, it puts the transported object to the
ground, and sends (via its SM) a Failed message to the
Task Manager containing information about the location of
the jar (i.e. the formula Jar002.PositionX = 12.5 AND
Jar002.PositionY = 1.3 AND Jar002.PositionZ
= 7). This allows the Task Manager to take an action in
order to complete the task. In this scenario there is another
service of the same (TransferObject) type available. So that,
TM arranges this service by passing, in the precondition,
the situation (the new position of the jar) received from
the damaged robot. The second service is executed, i.e.
the operative robot goes to the position, picks up the jar,
moves it to the destined position, and puts the jar on the
platform. Screen shots of Figure 4 show the following steps:
A – robot 1 approaches and grips the jar. B – robot 1
transports the jar. C – a failure; the drive of robot 1 is
out of order. D – robot 2 approaches the jar and grips it.
E – robot 2 transports the jar. F – robot 2 puts the jar
on the target platform. Figure 5 shows the complete FRP
protocol message exchange sequence while performing the
task in Scenario 1b. Failed TransferObject 1 service does
not participate in the re-arrangement process. The second
Arrange message is sent only to TransferObject 2 service.
The End message is sent to both services, indicating the
end of the transaction. More complex tasks (with failures
during execution) were also tested.

Conclusion. The SO-MRS architecture is a proposal
of a new information technology consisting of a generic
environment representation (upper ontology), specification of
the system components, and generic protocols for realizing
the system functionality, i.e. automatic accomplishing of
complex tasks, along with a protocol for failure handling
and recovery.
