Inspection of the Underwater Industrial Objects Using AUV Based on the Method of Feature Points Video Recognition

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Abstract. Automated inspection of seabed industrial equipment with the help of AUV assumes its navigational referencing to the inspection object with sub-metre accuracy. That accuracy cannot be achieved on the base of standard onboard navigation equipment. It is proposed to use the method of video recognition of feature points (FP) on the inspected equipment to solve this problem. The FPs are preliminarily determined on the models of objects and downloaded into the AUV control system in the form of three-dimensional sets (clouds). Ensuring stable high accuracy during continuous movement of AUV in inspected objects space is realized through regular updating of the coordinate referencing to the objects. The inspection procedure using this method consists of the following steps:

- the AUV mission specification (including downloading the FPs descriptions),
- launching the AUV and preliminary approach to the inspected objects,
- determining the optimal sequence for bypassing the inspected objects,
- performing the searching procedure for the next FP and navigational reference to it,
- subsequent inspection of the specified fragments of equipment.

At the same time, the logic of the mission execution provides for a dynamic change in the inspection plan in case of failure when any of the planned FP are detected. The paper presents the AUV control system algorithms that implement the described inspection scenario. The approach correctness was investigated using the mathematical modeling methods.

1. Introduction

More and more attention in the world is paid to the solution of the problems of subsea production systems (SPS) automated regular inspection with the help of AUV. A typical range of tasks for an SPS inspection includes [1]:

- contact (detailed) inspection using short-range equipment (sound-imaging devices, photo cameras);
- checking the compilation survey of the objects using long-range equipment;
- ecological inspection of the water mass and the sea bottom in the SPS vicinity;
- combined survey: detection and additional inspection of foreign small objects on the seabed near the SPS.

One of the AUV possible applications during an inspection is to determine the state of specified small fragments of equipment, for example, indicators, control elements, electrochemical checkpoints, etc. A
prerequisite for these works is to ensure accurate navigation of the AUV in relation to the inspected object.

Initially, the task of inspection was solved in the context of monitoring the state of long-distance communications (cables, pipelines). To perform such operations, it is necessary to ensure the determination of the pipeline laying direction on average, as well as the distance between the AUV and the object. In this case, information about the shape of the object cross-section (it is a circle, as usual) can be used to determine the distance. As a rule, the integration of information from sensors operating on the basis of various physical principles is performed to solve this problem. The method for AUV control during pipeline inspection is proposed in work [2]. It is based on the integration of data from the video camera, the multibeam echo-sounder (MBE), the subbottom profiler and the magnetic sensor. The authors cite the positive results of the experiment in the test pool. The work [3] describes an underwater inspection system for the AUV equipped with the triangulation laser system and the high-resolution camera. The laser system provides the determination of the distance to the pipeline and its orientation, while the camera takes overlapping images for subsequent mosaicing. The publications [4-6] describe a system based on the processing of magnetometer measurements for the detection and tracking of a submarine cable. The authors carried out computational experiments that demonstrate the efficiency of the proposed approaches. The works [7-9] present the results of the extended objects survey on the seabed using various equipment. In 2014 and 2016 the "Oceaneering" company surveyed pipelines sections of 511 and 467 kilometers long using AUV [7]. The AUV was equipped with the photographic system, the laser profiler and the MBE, but the pipeline was not automatically tracked. The results of pipeline inspection by means of the "Chercheur" AUV equipped with an "iCP" device for measuring magnetic and potential fields in order to assess the level of cathodic protection of metal products are presented in [8]. The work [9] presents the results of automatic inspection of several tens of kilometers of underwater metal cable using the AUV MT-98. Data aggregation from the electromagnetic finder and the video system was used to perform cable tracing. The works [10, 11] show the positive results of modeling the method for determining the position of the AUV relative to the pipeline based on the analysis of the visible shape of the laser beam, with the help of which the robot "illuminates" the object.

Attempts to carry out inspections of local SPS objects began somewhat later, since potentially providing navigation of the AUV relative to these objects is a more difficult task. This is due to the need to recognize objects of complex shapes, as well as to ensure the sub-meter AUV positioning accuracy near such objects. The use of standard on-board autonomous navigation devices in conjunction with the AUV hydroacoustic navigation equipment does not provide the required accuracy for these purposes. High-frequency hydroacoustic or laser scanning of an object with subsequent analysis of the resulting image can be used to achieve an accurate initial navigation reference. Further work near the object can be performed using the onboard high-precision inertial navigation system (INS) and Doppler log [3, 12]. However, the accumulating navigation error and the "noisy" operation of the Doppler lag near the SPS object of a complex shape do not provide the required accuracy, as a result.

High-precision navigation relatively to a local object can be achieved by processing video images received on board the AUV in real time (it is assumed, of course, that the transparency of the water allows the use of a video camera). The key task in this case is the recognition of an underwater object and/or its fragments. The work [13] presents the system for automatic execution of manipulation operations with objects using AUV. For this purpose, the AUV Girona 500 was equipped with the manipulator with 4 degrees of freedom (DOF). The operation of the AUV with mechanical toggle switches was shown after setting up its control system, based on the "training by demonstration" algorithm. The stabilization of the robot near the target (control panel of underwater equipment) was carried out using video data in the experimental pool. The recognition of a given picture was also carried out after training in this case.

However, the problem in a more general formulation (including the initial approach of the AUV to the object and the detection of the target equipment in its composition) was not solved in the experiment mentioned above. AUV search movements can be used to detect known fragments of an object (local reference point) in this case. An approach to solving the problem of small-sized objects inspection at the
sea bottom is described in [14]. First, objects are recognized on board the vehicle using side-scan sonar (SSS) data, and then a detailed survey is performed using a photosystem. The problem of the AUV initial approach to the object is solved in work [15] in a somewhat different way. There, an approach is proposed based on the combined use of the USBL APS and a video system for AUV accurate positioning (in this case, for the AUV automatic entry into the underwater dock). In [16], the authors consider an approach for tracking the desired trajectory (including trajectories near objects) using visual reference points, the global coordinates of which are known exactly, as well as adaptive neural networks for their recognition.

The problem, however, is that the global coordinates of SPS objects may not be known accurately enough due to errors in their determination during installation, as well as due to possible movements of these objects after installation. Therefore, it is advisable to carry out inspection work in a coordinate system linked to the object. Further, the article discusses a model solution of the problem of SPS fragments automated inspection, the main approach to the implementation of which is described in [1]. Among the features of the described approach, one can single out the use of short-range sensors for fulfillment a survey, which implies ensuring sub-meter accuracy in determining the position of the AUV with respect to the inspected object. The method of feature points (FP) recognition in photo/video images [17] is used for navigation referencing to an object. Further, the methods of visual stereo odometry [18, 19] are used to move near the object. In the water environment, the visibility area can be significantly limited, therefore, working with such a system involves the procedure for FP finding. It is proposed to use the AUV with a propulsion and steering complex that provides 5-DOF control to carry out the inspection. This allows the vehicle to stabilize a given position near the equipment.

2. Ensuring of coordinate referencing of AUV to inspected object

The method of precision coordinate reference to artificial underwater objects when one has their models was discussed in detail in [1, 17]. Let’s note the main features of this method.

The model to be explicitly to identify the object is deals as set of their feature point (FP) \( P\{P_1,…P_N\} \) and set of measured distances \( D_{model}^{model}\{d_{1,2}^{model},...d_{N-1,N}^{model}\} \) between them. Here \( d_{i,j}^{model} \) - distance between FP \( P_i \) and \( P_j \). The feature points are described in object’s coordinate system. The building of model is performing with taking into account the geometric information about the object. The numerated sequence (the set) of object’s 3D feature points is recording. One selects as FP preferable corner points which is potentially could be better recovered at photo images by detector program. The amount of such points depends on dimensions and geometric complexity of the object.

The coordinate referencing is based on three-stage processing of stereopictures with using of predefined object’s model. The main stages are set out below.

1) Selection and collation of the stereo pair of 2D-point features at the photo images. Building the set of 3D points \( C\{C_1,…C_m\} \) (3D cloud) by the collated points.

2) Recognition of the object’s points in 3D cloud of points using the algorithm of object points identification by the geometric model of the object. The algorithm is based on structural coherence principle. The input data for the algorithm are formed 3D-cloud of points and geometrical model of the object.

3) Coordinate referencing of AUV to the object, i.e. calculating a geometric transformation matrix from AUV coordinate system to object coordinate system. Matrix calculation is based on collation of several points from 3D cloud and from object’s model.

Coordinate referencing means calculation of geometric transformation matrix \( H_{AUV,object}^{AUV} \) to provide conversion from AUV coordinate system to object coordinate system. This task is being performed by traditional method of minimization of summary divergence of two collated sets of points when they combined in the same coordinate space \( \min \sum_{k=1}^{n} \| P_k - C_k H_{AUV,object}^{AUV}\| \), where \( P_k \) – k-th point in the sample \( S_{model}^{model} \), described in object coordinate system, and \( C_k \) – point in the sample \( S_{cloud}^{cloud} \), collated to point \( P_k \), which is described in AUV coordinate system.
Experiments in laboratory conditions have shown that precision of momentary coordinate reference to the object using the described method varies between 1.6-4 cm while carrying out the photo shot from a distance of 2-5m. While moving along the object with velocity 0.25 m/s using method visual odometry the accumulation of navigation error did not exceed 2 cm. Also, it was assumed that navigation error was reset during the passage of the next FP on average every 40 seconds (which corresponds to an average distance between the FPs of 10 m). Therefore, total precision of used method of navigation referencing approximately is of 3.6-6 cm.

3. Organization of AUV work

Described in [1] technique of survey was implemented on the base three-tier control system, which is using in IMTP FEB RAS developments [20]. The expanding of functionality of such system is being achieved by addition of modules-agents, which works on tactic level and coordination of their work is performing by mechanism of priorities.

Underlying the work of every agent is cycle of events processing to be emerging while module works. The events are timers ticks, receiving the messages and also activation of logical conditions, etc. The cycle of events processing starts after initialization of variables and works with predefined time interval (usually it is tens of milliseconds).

While decomposing the task of mission at subtasks-algorithms one must keep balance between reactive behaving and planning. In the framework of the current task the collection of the interacting agents must provide the following set of AUV actions:

- planning of sequence of bypassing the objects (if amount of them more than one);
- approach to the next object using standard navigation aids;
- performing the search movings near the object (with taking into account the conditions of visibility in work area) to for the purpose of detecting predefined collections of FP;
- correction the navigation system error after discovery of collection (cloud) of FP;
- inspection of specified object, i.e. switching to hanging mode and subsequent approximation with the object to specified distance. While hanging, AUV performs inspection of the object, which means photo-, video- and other data gathering.

To solve the described set of task there developed groupment of the tactical level agents, which composition and functions described below (agents are listed in order of increasing its priority).

- The "planner" loads mission description, plans and performs AUV movings between the objects (more precisely, between the collections of FP). When planning it uses "greedy" algorithm, i.e. it takes as a next point the nearest unsurveyed point. In case of failure of navigation reference to last queued point "Planner" replans its mission in the way to repeat inspection of unrecognized collections of FP.
- The "finder" loads mission description to get data about positions of collections of FP. The "finder" plans and performs search trajectory (the "flower") when AUV achieve the vicinity of the collection of FP to detect them and perform navigation reference. Performing the search movings are required because of accumulating error of AUV navigation system used to movements between SPS objects and also due to stochastic of time interval between actual capturing by AUV FP collection and its videorecognizing. If there videorecognizing fail occurred, then "finder" sends the report to the "planner".
- The "inspector" loads description of the mission to obtain the data about inspected points (IP) dislocation. After the navigation reference to the object "inspector" sequentially moves AUV to IPs and performs inspection (which means stabilizing position, "hanging" above IP and photo shooting). If SPS object (more precisely, collection of FP) has more than one IP, then "inspector" leads AUV to FP activates search procedure to minimization of accumulating error. The agent tells about the accomplishing of the inspection to the "finder".
4. Mission description
The mission for AUV about inspection of SPS objects is described in declarative style [21] and includes description of the objects and inspection tasks.

Inspected objects are described as 3D collections/cloud of FP together with their positions in coordinate system of the related SPS object. The feature points also linked to world coordinate system (however, with significant error) and also have individual text labels. There could be multiple collections of FP at the same object in different places. The tasks of inspection are formulated through inspected points (IP), which are linked to object coordinate system and also have own individual text labels.

The description of the mission is built as aggregate of FP and linked IP to them and also actions, which AUV must perform for every FP. Within the model experiments AUV actions were limited to photo survey of IP, therefore they was not detailed in the mission description.

5. Model experiments
The testing of algorithms of the mission agents was conducted at the base of previously developed modeling complex [22]. To investigate the AUV behavior was prepared model of external environment (Fig. 1), comprised of bottom surface (300×300m) and four production units on it.

![Figure 1. Model map with units and trajectory of survey in relation to object models.](image)

The used virtual AUV is equipped by imitator of videorecognizing system [17] and echosounder system. To determine of AUV coordinates standard navigation data fusion system had been used [23], consuming hydro acoustic navigation and dead reckoning system. The navigation system error had been imitated by addition normally distributed noise with zero mean and standard deviation equal to 0.00025 meters at 1 meter of AUV moving, that is corresponds to typical characteristics of such systems on modern AUVs. The modeled errors of hydroacoustic navigation system are set out in detail in [24].

The tasks of model experiments were included:
- assessment of the adequacy of control agent groupment which implement nested model of AUV behavior;
- debug on procedure of FP detection and performing navigation reference;
- checking the progress of survey mission in normal situation (mission is evolving according to the initially produced scenario);
- checking the mission progress in case of fail of FP recognition.

AUV mission consisted of inspections of collections of IP, depicted on Figure 1 as "IP_Nobj_Nip" (where Nobj – number of the object, and Nip – number of IP at the object). The database about inspected objects was included object collections of FP, depicted at Fig. 1 as "FP_Nobj".

After start and convergence with area of displacement SPS objects AUV had performed planning the sequence of bypassing the objects, giving the current navigation conditions (planned trajectory depicted at Fig. 2 by dashed line. Planned trajectory included sequential bypass of objects 1-4 and movement to
finish point. It is worth noting, on every object there described different amount of IP, that is reflected by shape of trajectory. Also planned trajectory doesn't include find movements of the AUV, which it performs to recognize of next FP - this movements are forming automatically by appropriate agent automatically, according to the situation.

![Figure 2. Planned and performed AUV movements.](image)

During the experiments, the vehicle moved along the trajectory depicted at Fig. 2 by solid line. FP on the Object 4 (first inspected) as it planned was recognized, with having its recognition been performed almost immediately, which caused non fulfillment of find movements in full. After performing the navigation reference there was inspected planned on this object FP, after that AUV moved to FP at the object 3 (the second in a row). FP recognition for this object failed, despite of fulfilled full find movements (Fig. 1 and 2). After that AUV immediately passed to survey of next objects (1 and 2), which held in normal mode.

To achieving targets of the mission in full there had been replanning of the trajectory. As result AUV performed returning to second object and repeating FP recognition, which had success. After the completion of the object's IPs inspection, AUV returned to pre planned finish point.

During the experiments, error of reference AUV to the object did not exceed 20 cm, that is illustrated by chart of error dynamics at Fig. 3. This allowed to perform photo survey of IPs with necessary accuracy.
Figure 3. Error of navigation reference of AUV to the inspected objects.

6. Conclusion
This work presents the results of modeling the process of automatic inspection of subsea production system objects by the AUV. The feature of developed methods is the using of stereo camera to precise navigation reference of AUV to inspecting objects. In doing so, it's assumed that geometric characteristics of the objects (their models) are known in advance. During the experiments functionality of AUV control algorithms, ensuring its performance, was confirmed. The experimental results showed the practical feasibility of the applied approaches.

Main difficulty in the implementation of navigation reference lays in the fact that the process of choosing (by a human) of FP at the stage of forming the SPS-object's model and process of identifying features in the images are relatively independent of each other. Experiments have shown that this leads to possible situations with a small number of identified points of the SPS-object's model, which negatively affects the probability of detecting FPs and the accuracy of the referencing.

The solution of the problem may lay in forming of the model in the process of AUV passing above the installed SPS. A joint analysis of the results of processing the obtained images by detector and the geometric model of SPS-objects will allow to include in the model only those FPs, that are more likely to be detected and compared by the detector on different projections of the scene. The generated model will be used for coordinate referencing directly during the inspection mission. Outlined tasks determine the directions of further researches.

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