HIERARCHICAL CONTROL OF MULTI-AUV SYSTEMS

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Abstract: *The paper highlights some approaches to fundamental problems of intelligent control of autonomous underwater vehicles (AUV) groups: logic-based approach to task management for inspection and protection of the water area, hybrid evolutionary models and algorithms for dynamic mission planning, and methods for rigorous analysis of discrete-continuous models of AUVs formations with discrete-event approach to AUV's operational modes switching. Hierarchical three-level architecture of control system is supposed and various models of AUV group functioning at the different control levels are considered.*

KEYWORDS: UNDERWATER VEHICLES, FORMATION CONTROL, LOGICAL CALCULUS, DISCRETE-EVENT SYSTEM, ROUTING PROBLEM, GENETIC ALGORITHM

1. Introduction

The exploration of the World Ocean's space and resources, particularly in the Arctic, is admitted to be one of the main research directions of the third millennium for high-developed countries having access to the sea. A significant role here is given to explorational autonomous underwater vehicles (AUV) with long autonomous functioning time, which are effective and the safest means for underwater research due to the absence of human aboard. Nowadays it is required to improve AUV dynamics, control autonomy and intellectuality to deal with the nondeterministic and unknown environment. At the same time, since it is impossible to predict underwater situations for implementing conventional programmed control, the development of new approaches to AUV groups control is the high priority problem which involves the design of intellectual computer-aided control systems.

The urgency of the group control problem for autonomous mobile robots is acknowledged by a large number of studies conducted in Western Europe, the USA, Japan, China and Russia. Complexity of this problem springs from, on the one hand, the requirement of developing methods and algorithms to control interdependent actions of individual robots achieving a common goal, and on the other hand, the necessity of implementing these actions real-time taking into account the variability of the environment. Hierarchical three-level architecture of control system is typically used to support complex AUVs group behavior. In what follows, we discuss various models of AUV group functioning and various approaches at different control levels implementation, including:

- a logic-based approach to task management for a group of AUV performing inspection and protection of the water area;
- online evolutionary approach for solving the maximum coverage patrol routing problem by a group of AUVs;
- the method for rigorous analysis and synthesis of digital control systems to maintain AUV formations
- a discrete-event approach to switching of operational modes of AUV groups in surveillance missions.

Logical calculus of positively-constructed formulas and discrete-event systems are used at the level of symbolic information processing, hybrid evolutionary models at the planning level, and discrete-continuous models at the execution level.

2. Execution level control algorithms

In this section, we derive sampled-data path-following and decentralized formation-keeping controllers. For this purpose, the dynamic model of AUV is borrowed from [1]. The kinematic and dynamics equations of the vehicle can be defined using a global coordinate frame $\{U\}$ and a body-fixed coordinate frame $\{B\}$. The kinematic equation of the AUV can be written

$$\begin{aligned} \dot{x} &= u\cos(\psi_B) - v\sin(\psi_B), \\ \dot{y} &= u\sin(\psi_B) + v\cos(\psi_B), \\ \dot{\psi}_B &= r, \end{aligned} \tag{1}$$

where x, y are the coordinates of the center of mass of the vehicle, ψ_B denotes the yaw angle, u and v are the surge and sway velocities expressed in $\{B\}$, respectively, and r is the angular yaw rate. Neglecting the equations in heave, roll and pitch, the equations for surge, sway and yaw can be presented [1] as

$$\begin{aligned} \mathsf{F} &= m_u\dot{u} + d_u, \\ 0 &= m_v\dot{v} + m_{ur}ur + d_v, \\ \mathsf{G} &= m_r\dot{r} + d_r, \end{aligned} \tag{2}$$

where $[\mathsf{F}\ \mathsf{G}]^T$ is the vector of force and torque applied to AUV.

To design path-following controller for a AUV, the conception of virtual target is exploited. Define the virtual target as a point P that moves along the path to be followed by the AUV. Associated with P, consider the corresponding Serret-Frenet frame $\{F\}$. As shown in [1] the dynamics of the virtual target in $\{F\}$ can be described by

$$\begin{aligned} \dot{s}_1 &= v_t\cos\psi - \dot{s}_a + \dot{\psi}_F y_1, \\ \dot{y}_1 &= v_t\sin\psi - \dot{\psi}_F s_1, \\ \dot{\psi} &= r + \dot{\beta} - \dot{\psi}_F, \end{aligned}$$

where s_1, y_1 are the coordinates of the vehicle in $\{F\}$, S is the signed curvilinear abscissa of P along the path, $\beta = \arctan(v/u)$ is the side-slip angle, $v_t = (u^2+v^2)^{1/2}$ is the absolute value of the total velocity vector; $\psi \equiv \psi_B + \beta - \psi_F$, ψ_F is an angle that defines the orientation of F with respect to U ($\dot{\psi}_F = c_c(s_a)\dot{s}_a$), c_c is the path curvature. We suppose that the virtual target moves along the path with a desired speed u_d and there is a restriction on the curvature of the path ($|c_c| \le \overline{c}_c$).

The path-following control problem can be formulated as followers. Given the AUV model (1)-(2) and a path to be followed, derive control laws for the force F and torque G that minimize the steady-state errors in variables y_1, s_1, and ψ.

To solve the problem, the following sampled-data control law is proposed:

$$\begin{gathered} \mathsf{F}(t) = \mathsf{F}_c + \mathsf{F}_s, \quad \mathsf{G}(t) = \mathsf{G}_c + \mathsf{G}_s, \quad t \in T_k \equiv [t_k, t_{k+1}), \\ \mathsf{F}_c = d_u, \quad \mathsf{G}_c = d_r + m_r(\dot{c}_c\dot{s}_a + c_c\ddot{s}_a - \hat{\ddot{\beta}}), \\ \mathsf{F}_s = (k_1\hat{s}_{1k} + k_2\Delta\hat{u}_k, \overline{\mathsf{F}}_s), \\ \mathsf{G}_s = (k_3\hat{y}_{1k} + k_4\hat{\psi}_k + k_5\Delta\hat{r}_k, \overline{\mathsf{G}}_s), \end{gathered} \tag{3}$$

where $t_k = kh$, $k = 0,1,2\ldots$, h is the control step; F_c, G_c are feedforward control terms aimed to cancel terms d_u, d_r in equations (2) and terms $\dot{c}_c\dot{s}_a$, $c_c\ddot{s}_a$, $\ddot{\beta}$ in the equation for variable $\Delta r @ r + \dot{\beta} - \dot{\psi}_F$; $\hat{\ddot{\beta}}$ is an estimate of acceleration $\ddot{\beta}$, $\ddot{\psi}_F = \dot{c}_c\dot{s}_a + c_c\ddot{s}_a$; F_s, G_s are feedback control terms, $\overline{\mathsf{F}}_s$, $\overline{\mathsf{G}}_s$ are the shares of maximum control force and torque reserved for stabilization, $\hat{s}_{1k}$, $\hat{y}_{1k}$, $\hat{\psi}_k$, $\Delta\hat{u}_k$, $\Delta\hat{r}_k$ are measurements of variables s_1, y_1, ψ, $\Delta u @ u - u_d$, Δr sampled at time moment t_k with some additive bounded errors; $(\sigma, \bar{\sigma}) = (\sigma)\min(|\sigma|, \bar{\sigma})$ is the saturation function; k_i are feedback coefficients ($i = \overline{1,5}$).

The formation control strategy considered here is based on the leader-follower approach [2, 3]. Focusing on a given leader-follower pair, denote the leader as l and the follower as f. Considering the leader as a virtual target for its follower, one can derive a kinematic model of the leader-follower pair in coordinates (s_1, y_1) as

$$\begin{aligned} \dot{s}_1 &= v_{tf}\cos(\psi_{Wf} - \psi_{Wl}) - v_{tl} + \dot{\psi}_{Wl} y_1, \\ \dot{y}_1 &= v_{tf}\sin(\psi_{Wf} - \psi_{Wl}) - \dot{\psi}_{Wl} s_1, \\ \dot{\psi}_{Wf} &= r_f + \dot{\beta}, \quad (\psi_W \equiv \psi_B + \beta). \end{aligned}$$

Let a desired position of the follower with respect to the leader in coordinates (s_1, y_1) be defined by vector $[s_1^*, y_1^*]^T$. The control law that provides stabilization of the desired position of the follower with respect to the leader can be defined as in (3) except for the feedback control terms defined as

$$\mathsf{F}_s = \mathrm{sat}(k_1 \Delta\hat{s}_{1k} + k_2 \Delta\hat{u}_{lfk}, \overline{\mathsf{F}}_s),$$

$$\mathsf{G}_s = \mathrm{sat}(k_3 \Delta\hat{y}_{1k} + k_4 \Delta\hat{\psi}_{lfk} + k_5 \Delta\hat{r}_{lfk}, \overline{\mathsf{G}}_s),$$

where $\Delta\hat{s}_{1k}$, $\Delta\hat{u}_{lfk}$, $\Delta\hat{y}_{1k}$, $\Delta\hat{\psi}_{lfk}$, $\Delta\hat{r}_{lfk}$ are estimates of $\Delta s_1 \equiv s_1 - s_1^*$, $\Delta u_{lf} \equiv u_l - u_f$, $\Delta y_1 \equiv y_1 - y_1^*$, $\Delta\psi_{lf} \equiv \psi_{Wf} - \psi_{Wl}$, $\Delta r_{lf} \equiv \dot{\psi}_{Wf} - \dot{\psi}_{Wl}$ at time moment t_k computed using measurements of the state vector of the follower and estimates of the state variables of the leader at t_k sent by the leader at t_{k-1} and received by the follower during the time interval T_{k-1}. As before, we need to design feedback coefficients k_i, $i = \overline{1,5}$.

The parameters of the proposed sampled-data control algorithms are synthesized with the use of sublinear vector Lyapunov functions (see, e.g., [4]). When designing controllers, we take into account uncertainties of the AUV's parameters, measurement errors, constraints on the control force and torque. Numerical computations have been performed for formations of large-sized AUVs. Simulation results for a circle-shaped formation is shown in Fig 1.

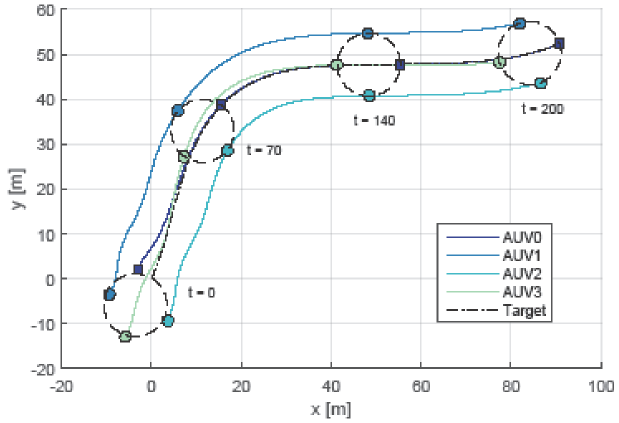

Fig. 1. *Formation trajectory*

The behavior of multi-AUV system in such missions as surveillance, monitoring, seafloor mappling, is rather complicated and includes the number of modes of operations where designed controllers are applied. As far as continuous dynamics of the leader and follower AUVs describes their predefined modes, switching between different modes of operation may be described in terms of discrete-event models. We propose discrete-event system (DES) and build supervisors for the top-level control of AUV operational modes switching as a reaction on environment changes, previous and current modes. Supervisory control theory (SCT) developed for discrete-event systems in 1980s [5], nowadays becomes powerful instrument in robotics applications. Recent implementations include single robots, robot groups [6] and robots formation control, swarm robotics [7], robots fights, etc. Considered as discrete-event system, system functioning is described with sequences of events, or words of some formal language. To implement SCT for AUVs formation control, first generators describing switching of a leader's and followers' operational modes are constructed. Then language specifications on DES behavior are constructed, determining required system functioning due to some constraints. Supervisor providing this specification designed after that. For reduction and proving of properties of constructed supervisors results from [8] are intensively used.

3. *Heterougeneous AUVs group routing*

During search and survey missions within specified water area a number of corresponded underwater works should be accomplished collaborative by AUVs assigned to that territory. In general, it is a vehicle routing problem (VRP) of task allocation and path planning under specific spatio-temporal constraints imposed by the uncertain nature of water environment and by inaccuracy of the measuring devices. In many real cases, like patrolling and guarding, taking samples and measurements, etc., underwater tasks require not the single but the periodic attendance of AUVs at scheduled intervals. Moreover, vehicles in the group may differ by their functionality (on-board equipment) which make them able to perform only specific sub-sets of tasks among all tasks of the mission. Thus, it is a problem of considerable practical interest to effectively route the heterogeneous group of AUVs in multi-objective missions of long-duration [9]. The problem of planning such a mission is to find a feasible group route ensuring, as far as possible, the well-timed and periodic execution of the majority of mission tasks. We propose a formalized AUVs group routing problem for the class of periodic multiobjective missions and suggest a hybrid evolutionary approach to address it effectively.

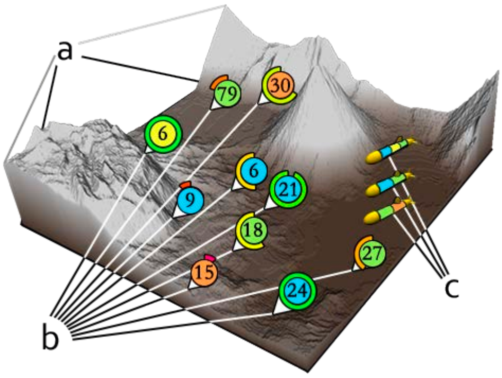

Fig. 2. *Schematic representation of the periodic multiobjective mission for the heterogeneous AUVs group*

Group mission planning is carried out: in an enclosed water area with a known seabed profile (Fig. 2, a); for a given finite set of control points (tasks) within allocated the water area (Fig. 2, b); by a heterogeneous group of multiple AUVs (Fig. 2, c); under a certain set of restrictions.

Depending on the equipment required to execute corresponded underwater works, each control point is assigned to one of the *task type* (colored circles on Fig. 2, b). Each control point also receives its *periodicity value* (numbers inside circles on Fig. 2, b) due to its predefined priority. Periodicity value defines the desired duration of a time interval between two successive attendances of any allowed AUVs. Color bars around each circle on Fig. 2, b represents remaining time interval to execute corresponded task in time.

The group of AUVs consists of functionally different vehicles, which may differ as by their cruising speed and range of hydro-acoustic communication channel, as by the set of on-board equipment (colored sections on Fig. 2, c). Thus, each vehicle is allowed to execute only those tasks that require affordable type of equipment. Group coordination here is provided only by transferring data between robots. Complete data alignment within the group could be achieved only if each pair of vehicles would be able to transfer data to each other directly or through other AUVs. In what follows the group routes are called *communicatively stable* if they guarantee the ability to align data regularly. *Communication stability* requirement arises due to the dynamic nature of underwater missions: some unexpected changes may occur in real time, making it necessary to adjust the current route (re-plan) in order to maximize the group efficiency in new conditions. The effectiveness of the group work is determined by regularity of scheduled tasks executions. Thus, the routing problem is to find a feasible communicatively stable group route that provides the minimum time of AUVs late attendance.

For a broad class of VRP there are no algorithms to solve it in polynomial time, which leads to the class of approximation algorithms allowing obtaining rational sub-optimal solutions in low computational time. We suggest a hybrid evolutionary approach featuring specialized genetic operators and solutions improvement heuristics to address both the expectable large-size of the problem and spatio-temporal constraints that primarily arise from the AUVs heterogeneity. Among the proposed heuristics are: three different construction heuristics (random sequential insertion and two parallel insertions) to ensure the initial population of solutions to both cover a significant portion of the search space and contain a variety of good solutions; two different variants of crossover and a multimode mutation. All heuristics are constructed to ensure the ultimate affordability of all vehicles to execute their routes. Group communication stability is also guaranteed by special verifying procedure. We also use the adaptation mechanism based on the ant colony optimization to vary inner parameters of the algorithm in order to maximize its efficiency on different steps of processing in those cases when some genetic operators begin to work significantly better than others do.

The high efficiency of the suggested approach is shown through a series of simulation studies in the simulation framework “AUV Mission Planner”.

2. The top-level control using PCFs logical calculus

Intellectualization of knowledge representation and processing on the top-level of AUV control system may be effectively based on the automated theorem proving (ATP) in the original machine-oriented language and logical calculus of positively constructed formulas (PCF). The PCF calculus was developed to solve control theory problems and described in detail in [10], and as the complete ATP method with functional symbols was introduced in [11]. Due to some features, the PCF calculus allows one to combine automatic proving with special heuristics (human knowledge and experience) customized for every given problem. Applying PCFs for planning the actions of AUVs, plans are constructed automatically while applying deduction of task specifications from the specification of functional capabilities of the AUVs. A question-answering procedure of the inference search significantly reduces restrictions of the logical approach to planning and control. Compared to other logical means of formalizing a subject area and deductions search, the PCF calculus has the advantages of expressiveness combined with compact knowledge representation, “natural” parallel processing, large-blockness, the least combinatorial complexity of deductions, and high compatibility with heuristics.

As an example of the PCF method usage we consider an approach to problem solving formalization for groups of autonomous underwater vehicles (AUVs) as the fragment of some centralized control system which continuously monitoring certain underwater area. Action sequences for AUVs and their groups are generated as a result of a first-order logic inference in automatic or interactive mode.

Let's consider the example of PCFs method application to describe and solve the following problem. Imagine a fragment of a centralized control system of groups of autonomous underwater vehicles that are continuously monitoring certain underwater area. Let's consider that there are two groups of autonomous robots (a_1 and a_2) in the area. Groups are composed of robots with different functionalities united in the likeness of tasks it can handle (for example, identification, sampling and manipulation, etc.). The groups control is maintained by the means of acoustic communication network with some central server (CS), that is allocated on the support ship. The CS operates automatically under the supervision of a human operator who can change group tasks and goals. Next, consider PCF language specifications of robots and CS as a possible parts of a larger system specification, focusing here on achieving a common goal of the two groups that will be reached in stages. It is required to achieve sub-goals to complete each stage. The completing or the inability to complete sub-goals is defined by events in the deductions search of formulas that specify the functionality of robot groups. If there is no way to complete a sub-goal, then a communication with CS is taking place to request re-planning. Sub-goals that are possible in our statement of the problem: object identification; carrying out additional actions with the object (sampling, communication); conducting defensive operations; loading of an object; docking with the object.

Groups of robots specifications in some initial moment of abstract time is described by the following base subformula:

$$\exists s_1, s_2, a_1, a_2, S(s_1), S(s_2), A(a_1), A(a_2), T(0)$$

Here $S(s_i)$ denote the set of atoms defining the state of groups $A(a_i)$.

The current functioning and tasks for groups are described by following questions to the base subformula:

$$\forall t\; T^*(t) - \exists\; T(t+1)$$

$$\forall x, t\; Patrol(t, s_i, a_i), T(t), See^{\#}(x)\; - \;\exists\; Find(t, x)$$

$$\forall x, t\; Find(t, x) - \;\exists\; \boxed{Task(t, x, a_i}$$

The first formula in the list of questions is the our method of the time moment counting in PCFs. It uses the atom with the symbol *, which means that if there is a successful answer to a question, then the corresponding atom must be removed from the base of facts. Thus, from the initial moment of time, in the cycle of the questions answering procedure, *T(1)* is added to the base instead of *T(0)*. Further, if the base is not refuted, *T(2)* will be added, and so on.

The second question, assume that one of the groups has the capability to detect objects. This option is checked with the help of the computational predicate *See(x)* denoted hereinafter in formulas by the symbol #. Truth values of the computational predicates are not established by the logical inference but by the actual state of environment. Thus, if detection sensors trigger successfully, the fact *See(Obj)* – a symbolized definition of the detected object – is added to the base. Then, for example, at time moment *n*, the second question has the answer, and the fact *Find(n, Obj)* will be added to the base.

Framed atom in the third question indicates the achievement of one of the sub-goals and the end of the deduction search. The communication with the CS is taking place. In our case, there is a request to the CS for further instructions after the object detection. The atom *Task(n, Obj,* a_i*)* is sent to the base of facts of the CS. This behavior is handled by the following question that might present in the list of questions on the CS:

$$\forall t, x\; Task(t, x, a_i) - \;\exists \boxed{Identify(x, a_i)}$$

After this question is answered, the fact *Identify (Obj,* a_i*)* will be sent to the coordinator of the group which sent the request. The system's further work is related with the study of the detected object. The first step is to determine whether the found object can present any danger. Suppose that the given task can be handled by group a_1. If there is no danger, the group a_2 can proceed to the task by robots with the ability to capture photos and videos.

Any object found in the area can be considered hazardous if it is moving and is not a local fauna representative, or if it contains any hazardous materials (pollution, underwater mines). For this task, there must be the following question subformulas in the list of questions of the a_1 group coordinator:

$$\forall x\; Identify(x, a_1) \begin{cases} \exists\; Moving^{\#}(x), NoAnswr^{\#}(x), NotFish^{\#}(x) \\ \exists\; Contamination^{\#}(x) \\ \exists\; Mine^{\#}(x) \end{cases}$$

$$\forall x\; Moving(x), NoAnswr(x), NotFish(x) - \;\exists \boxed{Danger_1(x, a_1)}$$

$$\forall x\; Contamination(x) - \;\exists \boxed{Danger_2(x, a_1)}$$

$$\forall x\; Mine(x) - \;\exists \boxed{Danger_3(x, a_1)}$$

The first question in this list splits the base, each new base subtree will correspond to the type of danger. Atoms with the symbol # request the corresponding sensors. In case of the negative analysis of the object, corresponding atoms in the base are removed (replaced by the constant *true*). According to the problem statement, only the one of the last three questions in the list can be answered, if it did, the deduction search stops and the type of danger – $Danger_j$ *(Obj, a_1)* –

is sent to the CS. If the deduction search fails, the group a_1 returns to the normal functioning, and the CS sends the task for the photo and video shooting to the group coordinator of a_2, which processes it with questions:

$$\forall x, t\; PhotoVideo(x, a_1), T(t) \begin{cases} \exists\; Photo(x, t) \\ \exists\; Video(x, t + 1) \end{cases}$$

$$\forall x, t\; Photo^{\#}(x, t), T(t)$$

$$\forall x, t\; Video^{\#}(x, t + 1), T(t)$$

The deduction search of two new bases will be successful, one after another. The first, at some moment *T(n)*, there will be a photo shoot as a result corresponding question application in the bottom list. After that, the second base's time will change to *T(n + 1)* and it will be possible to answer the last question, refuting the base and thereby completing the deduction search. The end of the deduction search means the achieving another sub-goal.

The presented statements describe some “life cycle” of two groups of robots. Further, by analogy, we can describe all possible situations and circumstances of the area's environment in the system. The plans of actions of the system are built and performed in automatic or interactive mode during the inference search. This example demonstrates a common approach to the planning problem using the method of PCFs.

5. Conclusion

In this paper various approaches to AUV group control on the different level of hierarchical control system were briefly discussed. Integration of the listed methods and algorithms into the one control system and its implementation in real life applications is the future work. The reported study was partly funded by RFBR according to the research project no.16-29-04238.

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