Hierarchical Control Development Environment: Requirements and Cases

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Abstract

The paper presents an approach to solve the problem of reducing complexity of representing hierarchical control systems of autonomous underwater vehicles (AUV), their models and interaction with external objects, as well as hardware in the form of information objects. For this purpose, a specialized environment for research is being developed, including a conceptual model of the subject area in the form of a formalized ontology, a domain specific language (DSL), a translator from this language, a system for transforming the obtained structures into software objects and data objects of other programming systems, thus providing the upper level of the software management.

Keywords

hierarchical control, intelligent technologies, intelligence and cognitive services, model driven architecture, autonomous underwater vehicles, convolutional neural network control

1. Introduction

The use of a group of Autonomous Underwater Vehicles (AUVs) has many advantages over a single robot, one of which is the ability to perform complex tasks such as ocean patrol and exploration, resource exploration and environmental monitoring. Thanks to the cooperation and information sharing between individual team members, an AUV group is more reliable and can adapt to different conditions and requirements. AUV groups can achieve more efficient resource utilization and mission accomplishment through distributed deployment and cooperative management, thereby improving the quality of research results. However, as the size of a group of AUVs increases due to the uncertainty in the parameters of each group member and the perturbations associated with its motion, more stringent requirements are imposed on the control strategy of AUVs in terms of accuracy, reliability, stability, etc. To solve the problems of controlling AUV formations under unknown and uncertain conditions, methods that are general enough to effectively deal with various group control problems have not yet been developed,

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and there is a lack of complete research software to implement these methods. The methods of automatic synthesis of hierarchical control of complex formations of AUVs are needed, which take into account individual peculiarities of AUV functioning, provide joint solution of tasks by a group of robots, limited acoustic communication channel, small choice of environmental sensors, partial or complete absence of a map of the work area, a priori uncertainty and variability of functioning conditions, inaccuracy of information received from measuring devices, possibly variable composition of the AUV grouping, significant limitations of the grouping of AUVs, and other factors. In this connection, the development of hierarchical control means is an urgent task of controlling heterogeneous (in terms of variants of control realization in a particular object) AUVs, especially in a dynamic environment with uncertainties. Deeper automation of AUV group control can be achieved through the use of artificial intelligence (AI) technologies. The paper proposes a way of developing hierarchical control systems, where the final control is built on the basis of discrete event model analysis, including lower level controls, and represents synthesized adaptive control strategies describing group behavior in the form of scenarios.

2. Problem statement

Currently, there is a steady tendency of increasing scientific interest in decentralized network-communication control of multi-agent systems. The most popular subject area of articles published on the subject can be named the research of various approaches to the construction of action planning systems for groups of autonomous robots performing survey and search operations, patrol missions and inspection tasks of various objects and structures. One of the most actively researched problems in the field of multi-agent systems is the control of formations of moving agents. More and more attention is paid to the tasks of controlling formations of aircraft [1], autonomous ground-based [2] and underwater robots [3]. Moreover, if in early studies more attention was paid to formations of aircraft and land-based robots, now the emphasis is shifting towards autonomous underwater robots, which is explained by the need to explore the largely unexplored depths of the World Ocean and its resources [4]. There is also a tendency to complicate the formulation of formation control problems: formulations with nonholonomic models of agents, nonlinear links between them, and variable topology of the information network are more and more often considered. Regardless of the approaches used, the following main directions of the current research in the field of AUVs formation control can be emphasized: development of robust and adaptive control systems for a group of AUVs taking into account the specifics of the underwater environment, e.g. the effect of lag and possible information loss during data transfer between AUVs, as well as the use of groups of AUVs in performing survey, search and protection missions.

Considering the dynamism and uncertainty of real-life environments and operating conditions, the research and development of autonomous control systems for mobile robots includes algorithmic control, PID control, neural network-based control, etc. Lower control levels respond to events generated by the upper levels, and switch in accordance with the main control goals. It is necessary to develop tools for recognizing the states of the system at the upper levels of control and implement control synthesis for the lower levels using, for example, logical inference and large language models. Lower-level control strategies will be determined by upper-level decisions in the form of specific behavioral scenarios, including path planning, generation of input data for pre-trained neural networks (graph convolution), control based on autonomous evolutionary games, and specific control signals for actuators. Therefore, it is needed to develop a multi-level hierarchical control system for a group of AUVs based on distributed control technology of event-triggered models, symbolic information processing and logical inference. To increase the stability of the system in an uncertain and complex environment and the accuracy of issued commands a switching control modes are to be implemented in accordance with control goals.

The path planning problem of a group of AUVs based on the hierarchical control requires developing appropriate distributed control strategies and algorithms by decomposing the path planning problem into several levels in order to realize flexible path planning and decision making for groups of AUVs at different levels. The development goals are to optimize global trajectory planning, reduce time to complete tasks, accuracy of local trajectory planning, implement dynamic obstacle avoidance with the collection of information about the environment, which will lead to increased autonomy and adaptability of AUVs in difficult conditions, increase the efficiency and autonomy of control and the quality of distribution tasks in the AUV group.

3. Approaches suggested

3.1. Discrete-event systems

To solve the problems arising in group control of AUVs, we propose to use an approach based on discrete-event systems (DES), in which the change of the system state occurs due to the occurrence of some events of various nature and character. In a hierarchical control structure, the system and its associated lower level controllers can be represented as DES for the upper control level.

Hundreds of journal publications and dozens of monographs are devoted to analytical studies of DESs. A detailed overview of the current state and trends in DES theory can be found in recent works [5], [6], [7]. Existing methods of DES study reflect the diversity of their models: finite automata theory, Petri nets, minimax algebras, Markov chains, and others. It was proposed a theoretical basis of a generalized approach to the study of DESs, which is potentially equally effective for any of the above models, based on the generation of a language (an infinite sequence of states and events) generated on the basis of the DES model. In doing so, the properties of formal regular languages are analyzed. In the specific cases, AUVs control may be represented as DES of low level and be a part of synthesized hierarchical control.

To control DESs containing events that can be prohibited from occurrence, the supervisory control theory (SCT) is used. The SCT was developed as a tool for constraining the behavior of the DES in accordance with a set of constraints defined by some formal specification. A detailed description of the SCT, outlining the results obtained in recent years, can be found in [8],[9]. The traditional area of application of DESs and SCT is the sphere of production processes, however, intensive research is currently being carried out on the features of the application of SCT in the field of robotics and robots group control. It seems reasonable to generalize the approach of analyzing DES properties in the direction of applying universal methods of mathematical systems' theory. For example, the reduction method proposed by S.N. Vassiliev and the method of logical-algebraic equations developed in ISDCT SB RAS may be applied. As a system for automating the above methods, the calculus of positively constructed formulas (PCFs) and the method for automatic theorem proving (ATP) developed on its basis may be used. The PCF calculus advantageously differs from the capabilities of other logical means of formalizing the subject area and searching for logical conclusions: expressiveness combined with compactness of knowledge representation, "natural" parallelism of its processing, large-block and less combinatorial complexity of inferences, high compatibility with heuristics. Previously, the basic problems of SCT including controllability checking, supremal controllable sublanguage of a given specification language construction and a monolithic supervisor realization were successfully solved using PCF-based approach [10]. Also, partially observed DES were studied, in which occurrence of some events are unavailable for observation [11].

3.2. Domain specific languages

Development of domain specific languages (DSL) is a popular direction in computer science of solving problems of abstract representation of a modeled object in terms close in level to the problem and methods of its solution. The main problem to be solved is the adaptation of the problem to the tools for its solution. In our case, we need a tool to describe different levels of DES, methods of control synthesis in terms of control theory, combinations of search strategies, physical models of AUVs, connection with external components (configurations), as well as assignments of specific DES of lower levels of control in the form of automata, transition rules, etc. Adaptation to tools is realized by methods of generative programming (Czernecki, Gorbunov-Posadov) with the help of various tools: compiler compilers, template programming, Model-Driven Architecture, MDA.

The potential of using MDA (Model Driven Architecture, a transformational approach to the design of software systems) in supporting complex scientific research is currently significantly underestimated. For example, in [12], an analysis of applications in the design of machine learning software systems shows that: the ideas of an abstract representation of data processing pipelines are not implemented to the extent that would significantly increase the productivity of research in machine learning, even less development of modeling and transformation of requirements for the pipeline. integration, automated deployment, monitoring. Existing solutions require greater maturity and better tool support; more attention must be paid to the scalability of solutions generated based on transformation. This problem arises due to the fact that the point of view on MDA is limited to the transformation of 1-to-1 models (one structure of the source model into one structure of the target) according to a certain set of rules (ATL, VRML technologies). We view the transformation process as a 1-to-n, n-to-m multi-level hierarchical process that models the human design process. Transformation is naturally represented as objects in the object-oriented logical language Logtalk [13].

To specify a language, the following models must be defined: syntax, semantics, and pragmatics. Syntax is modeled using grammars and translator implementation tools (flex, yacc; ANTLR4, and the like). Semantics is built on the basis of ontological modeling of the subject domain, using ontologies (Semantic Web) to represent the resulting conceptual models. The pragmatics of the language is realized in the algorithmic parts of the translators' description, and also often by means of a subsequent transformation procedure of some abstract intermediate representation, e.g. by applying MDA. MDA for a particular task is implemented as a procedure for generating derived information objects as a result of analyzing the original abstract information objects. The developed methods of MDA-transformation realizations also use logical inference. The main difference and advantage of the developed methods and technologies is the rigor of the results, the guaranteed nature of the obtained judgments and estimates, and, on the other hand, constructiveness, the possibility to bring the research "to the number".

It is important that the tasks under consideration are formulated directly in terms of engineering requirements to the system (direct specifications of dynamic quality indicators), and the results are also obtained in this form. Once the models under study have been reduced to a standard form, subsequent constructions and calculations will be performed to a large extent automatically, thus shielding from the researcher the special, rather mathematically complex methods used. The following techniques relate to the main principle of control synthesis for individual AUVs and their groups for specific types of AUV.

3.3. Convolutional neural network control

To solve the problem of planning the distribution of tasks between AUVs in complex multitasking environments, it may be proposed to create an integrated decision support system based on a graph convolutional neural network (GCN) enforced by classical methods of automatic logical reasoning e.g., in the PCF-calculus. It will be aimed at analyzing and predicting the optimal fit between AUVs and existing tasks, supporting for real-time interactive interaction with AUV control and planning systems, intuitive task monitoring, parameter tuning and visualization of behavioral patterns, providing effective and consistent decision support. To improve the tools for analyzing DES, implemented using logical means of inferring PCFs, the possibility of using convolutional neural networks in the heuristic apparatus for refuting PCFs should to be also explored.

The convolutional neural network control is implemented using standard steps: a) data preparation and preprocessing: collection of historical data on the results of AUV problem-solving execution, including task type, completion status, environmental parameters, etc.; b) construction of a GCN model for AUV and task conformance management to predict the best conformance to the management task plan at the AUV group level; c) the resulting plan is formally verified for compliance with task requirements and available resources using our knowledge-based system (KBS) based on PCFs; d) during plan execution, the KBS verifies compliance with constraints, task population structure. e) analyzing the obtained post-factum information to train further the neural network [14].

4. Path planning

The AUV path planning is realized at two levels: a) upper (global), where the AUV movement trajectories are designed, and b) lower (local), where new data obtained during the movement along a given path are taken into account. The upper level is constructed taking into account the task distribution, the space of possible states, and the environment constraints. It is supposed that the path is built with the help of logical prediction of the AUV motion in virtual time. To represent the model in the toolboxes, the corresponding DSL section is implemented. Global planning is realized by adapting the modern RRT method, using random sampling and fast exploration tree methods, obstacle avoidance algorithm, e.g. artificial potential field or dynamic window method. The resulting paths are locally optimized to match the local data. The planning algorithms are iterated into the overall hierarchical control mechanism in the form of intermediate levels. The problem of role allocation in a heterogeneous group of AUVs is solved using the method of modeling the behavioral revenue function in multi-agent systems organized in multilevel structures, which should have the property of consistency of the problem specification, and have prospectivity estimates close to the optimal ones.

The planning is implemented by means of the following steps: a) strategy derivation in a multilevel joint evolutionary game: conduct a multilateral multi-strategy evolutionary game in order to obtain a Nash equilibrium strategy; b) strategy evaluation: conduct a formal evaluation of the game results, compare individual AUV behavior plans and implement the adjustment of the game rules according to the results, i.e. adjust the game model to obtain results close to optimal. On the basis of the obtained evolutionary game models, the planning of AUV allocation to tasks is realized depending on the specific specifications of the task and AUVs. The logic of simulating the behavior between groups of AUVs allows using the methods of replicator dynamics, strategic balance points in the autonomous evolutionary game model. The fundamental idea is the adaptation of abstract control theory methods to the existing low level control techniques developed earlier; developing a new DSL capable to express various aspects of the domain and methods, transformation procedures for interpreting abstract language constructions in terms of specific case; development of parameter adjustment techniques for the existing techniques of control being a part of a hierarchical control.

5. Conclusion

In this paper we briefly described the idea of developing a tool for adaptation of control methods realizing different stages of solving control problems, into one common flexible mechanism of hierarchical control of groups of heterogeneous AUVs accordingly to a given task specification. The results obtained will significantly increase the efficiency of AUV use due to the implementation of learning and adaptation, synthesis and verification mechanisms when performing complex search and survey missions and joint problem-solving. The methods and means of synthesizing multilevel control developed will be based on the application of logical inference, where the process of generating information structures representing a particular class of control is described in the form of a first-order logical theory. The means of searching for logical conclusions in the calculus of positive constructed formulas (PCF) developed in Matrosov Institute for System Dynamics and Control Theory of Siberian branch of Russian Academy of Sciences, oriented to special classes of control models, having high compatibility with heuristics, allow eliminating the known problems of the logical approach to knowledge representation and processing, including in application to the construction of the upper level of control systems. In addition, the available means of logical inference are combined with models of problem-solving, resource allocation and control of constraints and parameters in the execution of plans, decision-making on control reconfiguration, and verification of results with respect to the task specification.

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