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A model-driven implementation to realize controllers for Autonomous Underwater Vehicles

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ABSTRACT

The goal of this study is investigated an implementation model, which is based on the real-time Unified Modeling Language (UML)/MARTE combined with the specification of hybrid automata and the Extended *Kalman* Filter (EKF) algorithm in order to intensively capture the development lifecycle of control and reuse it for controllers of Autonomous Underwater Vehicles (AUVs). To achieve this goal, the study is stepwise carried out as follows: the physical and dynamic model together with control architecture of AUVs are firstly adapted for developing entirely an AUV controller. The use-case model combined with the realization hypotheses of hybrid automata and the EKF algorithm are then specialized to closely gather the requirement analysis of control. The specializations of real-time UML/MARTE's features such as the 'capsules, ports and protocols' notation combined with the timing concurrency of evolution are next realized to precisely design structures and behaviors for the controller. The detailed design model is then converted into the implementation model by using object-oriented and open-source platforms in order to quickly simulate and realize this controller. Finally, a planar trajectory-tracking controller, which permits a miniature unmanned submarine to autonomously reaches and follows a planar reference trajectory, was deployed and tested with good reliability.

1. Introduction

Autonomous Underwater Vehicles (AUVs) are significant machines that made much progress in the ocean exploration to improve the human life. Their major breakthroughs resulted from successful developments of complementary technologies to overcome the challenges associated with autonomous operation in harsh environments. Most of the advances in AUV capabilities aimed at reaching new application scenarios and decreasing the cost of ocean exploration, by reducing ship time and automating the process of data gathering with accurate geo location. AUVs are also used by military operators for performing the complex underwater missions [1–3].

Within the autonomy architecture of AUVs are three main systems. These are: the guidance system, which is responsible for generating the trajectory for the vehicle to follow; the navigation system, which produces an estimation of the current state of the vehicle; and the control system, which calculates and applies the appropriate forces to manoeuvre the vehicle [4]. All three of these systems have their own individual tasks to complete, yet must also work cooperatively in order to reliably allow an AUV to complete its objectives. Hence, the AUV controller must take into account models with discrete events and continuous behaviors that can be considered as a Hybrid Dynamic System (HDS) of which global behaviors can be modelled by Hybrid Automata (HA) [5,6].

In addition, the immersion in an industrial control context makes that the development engineers must take into account costs and existing standards for analyzing, designing and implementing effectively the system. The customization and reusability are factors to be associated with the production of a new application in order to reduce its costs, resources and time development. According to the Object Management Group (OMG) [7], UML appeared to us to be essential for its visual object-oriented design support, which has been largely spread and appreciated in the software industry. However, UML is not well adapted to visualize, interconnection types between control objects or sub-systems for modeling industrial control systems. Furthermore, the Systems Modeling Language (SysML) [8], which is a UML profile for systems engineering, has been standardized by OMG. SysML supports the specification, analysis, design, verification and validation of a broad range of complex systems. But both UML and SysML lack the constructs for modeling time and duration constraints of the developed system. Hence, the real-time UML/MARTE version [9–11] is chosen to model in detail the analysis and design artifacts for real-time and embedded control systems, e.g. the AUV controller. This version also includes the 'capsules, ports, protocols, connectors' concepts that can be adapted by

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Nomenclature

AUVs	Autonomous Underwater Vehicles
CFD	Computational Fluid Dynamics
DoF	Degrees of Freedom
EKF	Extended *Kalman* Filters
GPS	Global Positioning System
HA	Hybrid Automata
HDS	Hybrid Dynamic Systems
IB	Integral Backstepping
IDE	Implementation Development Environment
IGCB	Instantaneous Global Continuous Behavior
IMU	Inertial Measurement Unit
LQR	Linear Quadratic Regulator
LOS	Line-Of-Sight
MARTE	Modeling and Analysis of Real-Time and Embedded Systems
MBSE	Model-Based Systems Engineering
MDA	Model-Driven Architecture
MDS	Measurement and Display System
MES	Marine Environment System
MPC	Model Predictive Control
MUS	Miniature Unmanned Submarine
NNPC	Neural Network Predictive Control
OMG	Object Management Group
OO	Object-Oriented
OOA	Object-Oriented Analysis
OOD	Object-Oriented Design
OOImpl	Object-Oriented Implementation
PID	Proportional-Integral-Derivative
SNAME	Society of Naval Architects and Marine Engineers
SysML	Systems Modeling Language
UKF	Unscented *Kalman* Filter
UPF	Unscented Particle Filter
UML	Unified Modeling Language

specializing a set of control capsules in precise behaviors and structures of the AUV controller.

The paper aims to implement a control model integrated the AUV dynamics for control into the real-time object paradigms, the specialization of HA features and the Extended *Kalman* Filter (EKF) algorithm, which can permit us to intensively realize and deploy the AUV controller, and also allow the designed and implemented control elements to be closely customizable and re-usable in the realization of new applications for various AUV types. The main methodology of this study is derived from our Model-Driven Architecture (MDA) specialization for controllers of quadrotor unmanned aerial vehicles [12] and object-unified approach for AUV controllers [13].

In the current model, the AUV dynamics and control structure are also adapted in detail for the AUV controller that are then combined with the models as follows: The Object-Oriented (OO) Analysis (OOA), OO Design (OOD) and OO Implementation (OOImpl) models; this control system permits an AUV to track a reference trajectory in the *Cartesian* space. Here, the OOA includes the use-case model specialized closely with an implementable function block diagram, the EKF algorithm, HA and its evolution hypotheses of realization to precisely capture the requirement analysis for an AUV controller; the OOD model is built on the identified OOA model by specifying the real-time UML/MARTE to entirely design the real-time control capsules with their timing concurrency of evolutions in detail. The detailed OOD elements is then converted into OOImpl models by using open-source platforms such as *Arduino* [14] in order to quickly simulate, realize and deploy the AUV controller. Finally, a planar trajectory-tracking controller of a miniature unmanned submarine was developed and taken on trial trip.

The paper is structured as follows: Section 2 brings the related works that have brought us to define a model-based design for AUV controllers. The AUV dynamics and control architecture are adapted in Section 3. Section 4 presents the details of an object-oriented implementation model to intensively realize AUV controllers, including the OOA, OOD and OOImpl components. Following this described model, in Section 5, it is applied to a case study. Conclusions and future works are reported in the Section 6.

2. Related work

In construction of AUV controllers, there are actually many applications that have used the traditional guidance, navigation and control methods combined with various soft computing techniques to optimally solve the computational complexity of the controller design. For example, Karimi [15] has presented a computational method using *Haar* wavelets to determine the piecewise constant feedback controls for a finite-time linear optimal control problem of a time-varying state-delayed; the use of *Haar* wavelet integral operational, product, and delay operational matrices enabled the approximate optimal trajectory and optimal control to be found by solving only linear algebraic equations instead of solving differential equations of the developed system. An analytical approach for estimating the AUV's hydrodynamic coefficients has been proposed by Sabet, Sarhadi and Zarini [16] that includes nonlinear *Kalman* filter algorithms implemented to estimate unknown augmented states, and shows the superior performance of Unscented *Kalman* Filter (UKF) in comparison with Extended *Kalman* Filter (EKF) for parameter identification of AUVs. Following the UKF technique, the decentralized UKF estimator has also implemented for dynamic state estimation of multi-area power systems by Qing, Karimi, Niu, et al. [17]; this study illustrated that the decentralized UKF delivered better estimation accuracy than the distributed UKF without consensus algorithm by imposing a few of communication costs between the neighboring areas. The optimal paths in environments with obstacles for underwater vehicles, which were computed by using a numerical solution of the Nonlinear Optimal Control Problem (NOPC) with nonlinear state space equations and non-quadratic performance index, could be found in [18]. A graph theory model with leader-follower architecture for multi-AUV systems based on second-order consensus protocol has been introduced by Xing, Zhao and Karimi [19]; in this work, more recent developments and contributions on enhancing the convergence rate was discussed, especially for the influences of control gains and network topology, and a collaborative navigation algorithm based on consensus-Unscented Particle Filter (UPF) algorithm was designed, which was shown to have a perfect filtering effect for the sake of eliminating noises during the navigation. Sarhadi, Ranjbar Noei and Khosravi [20] have introduced the models focused on design and hardware in the loop implementation of a novel adaptive control technique with dynamic anti-windup. In this research, the model reference adaptive control with integral state feedback is considered and is complemented with the potential to deal with input saturation by an adaptive anti-windup compensator, and the stability proof of the proposed controller is given using the *Lyapunov* theory, and the adaptation laws are extracted. Allotta, Conti, Costanzi, et al. [21] have presented a low cost AUV able to perform monitoring and patrolling missions; one of the main problem of AUVs is the necessity to use expensive sensors to localize the vehicle within the environment, the solution was proposed to face this problem by using low cost sensors and a related acoustic strategy. A hybrid-driven underwater glider model, hydrodynamics estimation, and an analysis of the motion control have been introduced in [22] that included the estimation of hydrodynamic coefficients by using the Strip theory and Computational Fluid Dynamics (CFD), and