An Enhanced Situational Awareness of a Mission for an Autonomous Underwater Vehicle by Multirate Control

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Abstract: - This paper focuses on a critical component of the situational awareness (SA), the neural control of depth flight of an autonomous underwater vehicle (AUV). Constant depth flight is a challenging but important task for AUVs to achieve high level of autonomy under adverse conditions. The fundamental requirement for constant depth flight is the knowledge of the depth, and a properly designed controller to govern the process. With the SA strategy, we proposed a multirate control procedure to address the dynamics variation and performance requirement difference in various stages of AUV’s trajectory for a nontrivial mid-small size AUV “r2D4” model. Two adaptive neural network controllers are designed for fast and stable diving maneuvers of this AUV model. This control strategy for chosen AUV model has been verified by simulation of diving maneuvers using software package Simulink and demonstrated good performance for fast SA in real-time search-and-rescue operations.

Key-Words: - Autonomous underwater vehicles, depth flight, multirate control, neural networks, simulation, situational awareness.

1 Introduction
Situation awareness has been formally defined as “the perception of elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future” [1]. As the term implies, situation awareness refers to awareness of the situation. Grammatically, situational awareness (SA) refers to awareness that only happens sometimes in certain situations.

SA has been recognized as a critical, yet often elusive, foundation for successful decision-making across a broad range of complex and dynamic systems, including emergency response and military command and control operations [2].

The term SA have become commonplace for the doctrine and tactics, and techniques in the U.S. Army [3]. SA is defined as “the ability to maintain a constant, clear mental picture of relevant information and the tactical situation including friendly and threat situations as well as terrain”. SA allows leaders to avoid surprise, make rapid decisions, and choose when and where to conduct engagements, and achieve decisive outcomes.

In [4] a three stage flight control procedure using three autonomous control subsystems for a nontrivial nonlinear helicopter model on the basis of equations of vertical motion for the center of mass of helicopter was proposed. The proposed control strategy has been verified by simulation of hovering maneuvers using software package Simulink and demonstrated good performance for fast SA in real-time search-and-rescue operations.

This paper concentrates on issues related to the area of [4], but demonstrates another field for application of these ideas, i.e., research technique using hybrid multirate control system modeling and simulation on the basis of state-space equations of motion for chosen model of an autonomous underwater vehicle (AUV) for fast SA.

The AUV provides the commander with a number of capabilities including:
- Enhanced SA.
- Target acquisition.
- Enhanced management capabilities (assessment of surface damage and visualization of blockage far and near).

Some conditions for conducting underwater reconnaissance with AUVs are as follows.
- Time is limited or information is required quickly.
- Detailed reconnaissance is not required.
- Extended duration surveillance is not required.
- Target is at extended range.
- Threat conditions are known; also the risk of collisions with a rough-surfaced seabed is high.
Verification of a target is needed.
Relief of seabed restricts approach by large-scale underwater vehicles.

A mid-small size AUV offers many advantages, including low cost, the ability to fly at constant depth levels within a narrow space and the unique diving characteristics.

The fundamental requirement for diving control is the knowledge of the depth under the sea surface, and a properly designed controller to govern the diving.

Optimum values for PID (proportional–integral–derivative) controllers are derived via the simulations of AUV “r2D4” motion based on the closed-loop vehicle dynamics [5].

The characteristics of an AUV’s motion depend on mode of maneuvering, forward speed, instantaneous attitude, and outside appendages such as measuring instruments. In addition, it is hard to model the system disturbances, cross-flow and the coupling effects. Due to these reasons, the adaptive neural network controllers are needed to control AUV’s motions.

In this paper our research results in the study of depth controls of AUV which make such SA task scenario as "go-search-find-return" possible are presented.

The contribution of the paper is twofold: to develop new schemes appropriate for SA enhancement by hybrid multirate control of AUV’s trajectory in real-time search-and-rescue operations, and to present the results of diving maneuvers for chosen multirate AUV’s model for fast SA in simulation form using the MATLAB/Simulink environment.

2 AUV’s Model

The AUV “r2D4” [5] is a mid-small size AUV designed to conduct survey of underwater hydrothermal vents. As is analogized from its name, maximum depth of operation is 4000 m. This AUV is 4.4m in length, 1.08m in breadth, and 0.81m in height. It weighs 1630 kg with payload. The maximum speed of given AUV is 1.544 m/s.

Consider the AUV “r2D4” model [5] in terms of a state variable representation as follows:

\[ \dot{x}_1 = A_1 x_1 + B_1 u_1 \]
\[ y_1 = C_1 x_1 \]
\[ \dot{x}_2 = A_2 x_2 + B_2 u_2 \]
\[ y_2 = C_2 x_2 \]

where
\[ u_1 = \begin{bmatrix} n_w & n_{q_y} & n_{r_y} & \delta_n & \delta_y \end{bmatrix}^T, \]
\[ u_2 = \begin{bmatrix} \delta_{n_r} & \delta_{q_y} & \delta_{r_y} \end{bmatrix}^T, \]
\[ x_1 = \begin{bmatrix} u & w & q & \theta \end{bmatrix}^T, \]
\[ x_2 = \begin{bmatrix} \nu & p & r & \phi \end{bmatrix}^T, \]
\[ u(m/s), v(m/s), w(m/s) \] are surge, sway and heave velocities;
\[ \rho (\text{rad}/s), \sigma (\text{rad}/s), r(\text{rad}/s) \] are angular velocities of roll, pitch and yaw motions;
\[ n_w, n_{q_y}, n_{r_y}, n_{n_r}, n_{q_y}, n_{r_y} \] are numbers of revolutions per second of main, fore-vertical and rear-vertical thrusters;
\[ \delta_{n_r} (\text{rad}), \delta_{q_y} (\text{rad}), \delta_{r_y} (\text{rad}) \] are deflection angles of main thruster, right and left elevators;
\[ \phi (\text{rad}), \theta (\text{rad}) \] are roll and pitch displacements;

\[ A_1 = \begin{bmatrix} -0.1465 & 0.0263 & 0 & -0.0006 \\ 0.0683 & -1.3658 & 3.8905 & 0.1900 \\ 0.0062 & -0.0132 & -1.2340 & -0.0832 \\ 0 & 0 & 1 & 0 \end{bmatrix}, \]
\[ B_1 = \begin{bmatrix} 0.0491 & 0 & 0 & 0 \\ 0 & 0.0112 & 0.0006 & 0.0679 & 0.0679 \\ 0 & -0.0029 & 0.0018 & -0.0979 & -0.0979 \\ 0 & 0 & 0 & 0 \end{bmatrix}, \]
\[ A_2 = \begin{bmatrix} -0.5266 & -0.0024 & -0.8046 & -0.0052 \\ -3.5308 & -4.7897 & 8.0281 & -10.5544 \\ -0.1472 & -0.0332 & -0.4068 & -0.0722 \\ 0 & 1 & 0 & 0 \end{bmatrix}, \]
\[ B_2 = \begin{bmatrix} -0.0335 & -0.0011 & 0.0011 \\ 0.0244 & -2.1704 & 2.1704 \\ 0.0486 & -0.0149 & 0.0149 \\ 0 & 0 & 0 \end{bmatrix}, \]
\[ C_1 = C_2 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}. \]

In [6], the derivative of yaw displacement $\psi$ of AUVs could be expressed as
\[ \dot{\psi} = (q \sin(\phi) + r \cos(\phi))/\cos(\theta) \]

Then, we have
\[ \psi(t) = \int_0^t \dot{\psi}(t) dt + \psi(0) \]
3 Multirate Subsystems

In [7] it is offered the approach to design of multirate linear systems, which consist of naturally grouped entrance and target signals that are caused by their characteristic frequencies.

Consider a state-space model of a linear continuous-time system
\[ \dot{x}(\tau) = Ax(\tau) + Bu(\tau) \]
\[ y(\tau) = Cx(\tau) \]
where \( x(\tau) \in \mathbb{R}^n, u(\tau) \in \mathbb{R}^m, y(\tau) \in \mathbb{R}^p \) are the state, control input and output vectors, respectively.

Suppose that we consider the linear transformation \( q(\tau) = T x(\tau) \), where \( T \) is a nonsingular matrix. It is easy to see that (7)-(8) are transformed into the equations
\[ \dot{q}(\tau) = J_c q(\tau) + \bar{B} u(\tau) \]
\[ y(\tau) = \bar{C} q(\tau) \]
where
\[ J_c = T A T^{-1}, \bar{B} = T B, \bar{C} = C T^{-1} \]

The equations (9)-(10) may be written in terms of submatrices as
\[ \dot{z}_1(\tau) = A_1 z_1(\tau) + B_1 u(\tau) \]
\[ \dot{z}_2(\tau) = A_2 z_2(\tau) + B_2 u(\tau) \]
\[ \dot{y}(\tau) = C_1 z_1(\tau) + C_2 z_2(\tau) \]
where
\[ z_1(\tau) = \begin{bmatrix} z_1(\tau) \\ z_2(\tau) \end{bmatrix}, \]
\[ J_c = \begin{bmatrix} A_1 & 0 \\ 0 & A_2 \end{bmatrix}, \bar{B} = \begin{bmatrix} B_1 \\ B_2 \end{bmatrix}, \bar{C} = \begin{bmatrix} C_1 & C_2 \end{bmatrix} \]

**Definition 1:** A function with a large derivative that is quickly decreasing is said to be the "fast" function; a function with a small derivative that is slowly decreasing is said to be the "slow" function. A function is said to be the "intermediate" function if the derivative of this function is intermediate between small and large values.

It is clear that in an asymptotically steady system the "fast" modes related to the large eigenvalues are important only within a short interval of time \( 0 \leq \tau_f \leq \tau_\beta \). After this interval \( (\tau_f, \tau_\beta) \) they are insignificant and the behavior of the system can be described by its "intermediate" and "slow" modes.

Let us consider the first time interval: \( 0 \leq \tau_f \leq \tau_\beta \). The equation (11) can be rewritten as
\[ \dot{z}_i(\tau) = F(z_i(\tau), u(\tau)) \]

Applying a method of the Euler, the solution (11) on the considered interval is given by
\[ z_i(\tau_f) = z_i(0) + \tau_f F(z_i(0), u(0)) \]

According to Definition 1 variable \( u(\tau) \) can be considered as "slow" function of time on this interval. Assuming that \( z_i(0) = 0 \), from (11) and (16), we have
\[ z_i(\tau_f) \approx \tau_f B_i u(\tau_f) \]

Similarly, applying a method of the Euler to (12) and counting that \( z_2(0) = 0 \), we find
\[ z_2(\tau_f) \approx \tau_f B_2 u(\tau_f) \]

Further, from (13), (14), (17) and (18), we find that the state equations for the "fast" subsystem may be written as
\[ \dot{z}_j(\tau_f) = A_j z_j(\tau_f) + B_j u(\tau_f) \]
\[ y_j(\tau_f) = C_j z_j(\tau_f) \]

where
\[ A_j = A_1, B_j = B_1, C_j = C_1, D_j = D_1 \]
\[ z_j(\tau_f) = m_j(\tau_f), u_j(\tau_f) = m_j(\tau_f), y_j(\tau_f) = y_j(\tau_f) \]

Let us consider the second time interval: \( \tau_{\beta} < \tau_{\beta'} \). According to Definition 1, the variable \( z_i(\tau) \) can be considered as a "fast" function, achieving on this interval a steady meaning. Hence, assuming that \( z_i(0) = 0 \), from (13), we find
\[ z_i(\tau_f) \approx -A_j^{-1} B_j u(\tau_f) \]

The implicit formula of the Euler for \( z_i \) from (11) can be written as
\[ \dot{z}_i(\tau_f) = \frac{z_i(\tau_f) - z_i(0)}{\tau_f} \]

If we now substitute (22) into (11) and assume that \( z_i(0) = 0 \), we have
\[ z_i(\tau_f) \approx \tau_f[I - A_j^{-1} B_j u(\tau_f)] \]

From (12), (14), (21) and (23), we find that the state equations for the "intermediate" subsystem may be written as

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The system (1)-(2) is described by

\[
\begin{align*}
\dot{z}_i(t_r) &= A_i z_i(t_r) + B_i u_i(t_r) \\
y_i(t_r) &= C_i z_i(t_r) + D_i u_i(t_r)
\end{align*}
\] (24)

where

\[
A_i = A_i, B_i = B_i, C_i = C_i, D_i = C_i [I - r_i A_i]^{-1} B_i - C_i A_i^{-1} B_i,
\]

\[
z_i(t_r) = z_i(t_r), u_i(t_r) = u(t_r), y_i(t_r) = y(t_r).
\]

We now proceed to the consideration of the third interval mentioned above \( t_r \).

According to Definition 1, it is possible to consider variable \( z_2 \) as an "intermediate" function, achieving on this interval steady meaning. Hence, assuming that \( \dot{z}_2(t_r) \approx 0 \), from (12), we have

\[
z_2(t_r) \approx -A_2^{-1} B_2 u(t_r)
\] (26)

According to Definition 1, the variable \( z_3 \) can be considered as a "fast" function of time, achieving on this interval steady meaning. Hence, assuming that \( \dot{z}_3(t_r) \approx 0 \), from (13), we find

\[
z_3(t_r) \approx -A_3^{-1} B_3 u(t_r)
\] (27)

Further, from (11), (14), (26) and (27), we find that the state equations for the "slow" subsystem may be written as

\[
\begin{align*}
\dot{z}_1(t_r) &= A_1 z_1(t_r) + B_1 u_1(t_r) \\
y_1(t_r) &= C_1 z_1(t_r) + D_1 u_1(t_r)
\end{align*}
\] (28)

where

\[
A_1 = A_1, B_1 = B_1, C_1 = C_1, D_1 = -C_1 A_1^{-2} B_1 - C_1 A_1^{-1} B_1,
\]

\[
z_1(t_r) = z_1(t_r), u_1(t_r) = u(t_r), y_1(t_r) = y(t_r).
\]

Next, the matrices of the "intermediate" subsystem (24)-(25) for system (1)-(2) are computed

\[
A_h = [-0.1458]
\]

\[
B_h = \begin{bmatrix} 0.3933 & -0.0007 & 0.0017 & -0.0750 & -0.0750 \end{bmatrix}
\]

\[
C_h = \begin{bmatrix} 0.1245 \\ 0.0036 \\ -0.0016 \\ 0.0109 \end{bmatrix}
\]

\[
D_h = \begin{bmatrix} 0.0012 & 0.0010 & -0.0007 & 0.0365 & 0.0365 \\ 0.0021 & 0.0025 & 0.0038 & -0.1365 & -0.1365 \\ 0.0030 & -0.0009 & 0.0005 & -0.0285 & -0.0285 \\ -0.0385 & -0.2333 & 0.0138 & -0.7599 & -0.7599 \end{bmatrix}
\]

The "slow" subsystem (28)-(29) of system (1)-(2) is specified by

\[
A_h = [-0.0706]
\]

\[
B_h = \begin{bmatrix} 0.0319 & -0.0213 & 0.0126 & -0.6928 & -0.6928 \end{bmatrix}
\]

\[
C_h = \begin{bmatrix} -0.0039 \\ -0.0083 \\ 0.01246 \end{bmatrix}
\]

\[
D_h = \begin{bmatrix} 0.3359 & -0.0004 & 0.0012 & -0.0534 & -0.0534 \\ 0.0093 & 0.0008 & 0.0049 & -0.1940 & -0.1940 \\ -0.0040 & -0.0027 & 0.0016 & -0.0863 & -0.0863 \\ 0.0291 & 0.0022 & -0.0012 & 0.0653 & 0.0653 \end{bmatrix}
\]

The constant matrices of the "fast" subsystem (19)-(20) for system (3)-(4) are given by

\[
A_f = \begin{bmatrix} -2.3681 & 2.2258 \\ -2.2258 & -2.3681 \end{bmatrix}
\]

\[
B_f = \begin{bmatrix} 0.0383 & -0.9851 & 0.9851 \\ -0.0384 & -0.5084 & 0.5084 \end{bmatrix}
\]

\[
C_f = \begin{bmatrix} 0.0035 & -0.0082 \\ 1.7269 & 0.9227 \\ 0.0135 & 0.0017 \\ -0.4525 & 0.8769 \end{bmatrix}
\]

\[
D_f = \begin{bmatrix} -0.3395 & -0.0183 & 0.0183 \\ -0.0642 & -0.0013 & 0.0013 \\ 0.4815 & -0.0075 & 0.0075 \\ 0.5098 & 0.0009 & -0.0009 \end{bmatrix}
\]

The "intermediate" subsystem matrices (24)-(25) for system (3)-(4) are
In terms of (28)-(29) for system (3)-(4), the “slow”-subsystem matrices are

\[
A_s = \begin{bmatrix} -0.1760 \\ -0.0023 \end{bmatrix},
B_s = \begin{bmatrix} -0.0573 \\ -0.0072 \end{bmatrix},
C_s = \begin{bmatrix} 0.0412 \\ 0.0247 \\ 0.0072 \end{bmatrix},
D_s = \begin{bmatrix} -0.3388 \\ 0.0018 \\ 0.0167 \\ -0.2034 \end{bmatrix}
\]

Then, we have

\[
x(t) = \int_0^t \dot{x}(t) dt, 
\]

where

\[
x(0) = 0, y(0) = 0, z(0) = 0.
\]

From (1)-(6), (30)-(31) we can see that the attitude vector \([x \ y \ z]^T\) for given model of an AUV can be computed.

## 5 Simulation Results

Since the depth of an AUV is most critical for diving maneuvers, the control mechanization of depth trajectory profile will be demonstrated.

Consider the control of an AUV “r2D4” decomposed multirate model for the case of hybrid control system with two autonomous adaptive neural controllers.

The goal of the following simulations is twofold. First, we verify that these neural network controllers are able to control the diving trajectory. Second, we observed the effect of enhancing SA because by the variation of such trajectory parameters as maximal depth and constant depth flight easily can be changed the possible diving trajectory of AUV.

Initial conditions and desired constant depth levels for multirate control subsystems are chosen to be:

\[
\begin{bmatrix} z_1 \\ z_2 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}, \quad \begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}, \quad \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix},
\]

where

\[
\begin{bmatrix} j_{31} = -\sin(\phi), \\
\end{bmatrix}
\]

\[
\begin{bmatrix} j_{32} = \cos(\phi)\sin(\phi), \\
\end{bmatrix}
\]

\[
\begin{bmatrix} j_{33} = \cos(\phi)^2. \\
\end{bmatrix}
\]

Some advantages of this example are as follows.

- Possibility to consider a rough-surfaced seabed in a place of a constant depth flight.
- Possibility of hovering in the various constant depth levels.
In1
In2
In3
In4
Out1
Yaw 2
Terminator1
Terminator
Switch IS4
Switch IS3
Switch IS2
Switch IS1
Switch FI4
Switch FI3
Switch FI2
Switch FI1
Switch 6
Switch 3
x' = Ax+Bu
y = Cx+Du
State-Space Slow 4
State-Space Slow 3
State-Space Slow 2
State-Space Slow 1
State-Space Intermediate 4
State-Space Intermediate 3
State-Space Intermediate 2
State-Space Intermediate 1
1/s
Integrator6
1/s
Integrator5
1/s
Integrator4
1/s
Integrator3
1/s
Integrator2
1/s
Integrator1
12:34
Digital Clock 5
12:34
Digital Clock 4
12:34
Digital Clock 3
12:34
Digital Clock 2
12:34
Digital Clock 1
12:34
Digital Clock
D2R
 Degrees to Radians3
D2R
 Degrees to Radians2
D2R
 Degrees to Radians1
D2R
 Degrees to Radians
Fig. 1. Block diagram of hybrid control system.

Fig. 2. Block scheme of an ADALINE NN.

Fig. 3. AUV’s trajectory of a mission.
Fine and simplified adjustment of adaptive neural controllers for any changes of desired constant depths.

From the simulation studies of diving tests, the following can be observed:

- By following the proposed methodology, the AUV “r2D4” model structure (1)-(4) is decomposed into three groups of subsystems: the “fast” subsystems used in the initial phase of trajectory (downward or upward motions), the “intermediate” subsystems used in the middle phase of trajectory (forward motion), and the “slow” subsystems used in the final phase of trajectory (circular motion). Note that the obtained subsystems not only have reduced dimensions of state-space matrices, but also various speeds of actuation (fast, intermediate and long response times) and are completely shared in time. Further analysis of the decomposed subsystems can be produced separately with the help of modern computer-aided control analysis software.

- The 3-D display forms give a researcher an immediate view of AUV “r2D4” motion with a range of such parameters as maximal depth and constant depth flight. This enhances the researcher’s understanding of diving maneuvers.

- The multirate control works more qualitatively than the single-rate control.

These results support the theoretical predictions well and demonstrate that this research technique would work in real-time diving conditions.

6 Conclusions

A new research technique is presented in this paper for enhanced SA in possible AUV’s missions.

The need for accurate and directionally stable diving for AUV class autonomous vehicles has increased morbidly for critical situations in real-time search-and-rescue operations for fast SA.

The effectiveness of the proposed research technique has been verified in field of diving simulation tests for chosen model of the AUV “r2D4” using software package Simulink. Its performance of multirate motion control is good and has the advantages over conventional single-rate motion control under the same conditions.

From the applications viewpoint, we believe that this flexible and effective multirate control is a powerful approach for enhanced SA in applications to AUV class autonomous vehicles in real-time search-and-rescue operations.

Future work will involve further validation of the performance of the proposed research technique and exploring other relevant and interesting AUV’s missions.

References: