A comparison of digital AUV platform’s result with lake experiment’s

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Abstract—A semi-physical virtual reality system applying to AUV (Autonomous Underwater Vehicle) control study is presented in this paper. This system is composed of three nodes: (1) control node for receiving sensors information and sending control command, (2) virtual model node for virtual devices and sensors and (3) vision node for virtual ocean environment information and displaying the posture of AUV. The control node can be both linked to the real hardware or actuators dealing with a real mission, and linked to the virtual node for purpose test. The experiment results showed that, (1) the horizontal plane controller parameter performed well in the real lake test, while the vertical plane controller parameter should be little changed. (2) the stable and dynamic performance almost are the same between the virtual and real experiments.

I. INTRODUCTION

AUV (Autonomous Underwater Vehicle) plays an important role both present and future. The development of an AUV is not a simple task. For not only the vehicle needs intelligent software architecture responsible for driving the vehicle during the mission, but also its software must be able to deal with unstructured and uncertain environments in real time. In order to build this kind of software, an intensive set of experiments in an exhaustive number of ocean environments is necessary. Nevertheless, testing in real environment is expensive in both resources and man-hours. Hence, there exists the following problem: (1) the number of real experiments must be reduced while at the same time intensive experiment should be carried out; (2) The obstacle of unknown ocean environments (include bottom terrain, current, temperature, salinity etc.) frustrate almost anyone who engaged in AUV research on the spot. For these reasons, a semi-physical Digital AUV (DAUV) platform implementing the virtual vehicle and the virtual world are desirable tools for research. In our laboratory we have developed a DAUV in such a way that it can distinctly deal with the real vehicle or the virtual one. The advantages of the system include testing AUV software before real experiment, verification kinds of planning algorithmic and its cheap cost.

More and more attentions and focus on the development graphical simulators in the underwater vehicle community. The necessity of these kinds of tools was clearly shown by D. P. Brutzman [1]. Several researches extended this concept to include multiple vehicles working in either a virtual or hybrid virtual/real environment. In 1991, Pappas etc. developed the first hardware in loop system. Choi etc. presented a distributed virtual environment collaborative simulator for underwater vehicles ODIN etc. [2]. Kuroda etc. [3] developed a Multi-vehicle Graphical Simulator for the twin-Burger underwater vehicles. P. Ridao etc. [4] design a distributed environment for virtual and/or real experiment for underwater robots. In a similar way, S. Chappell etc. (Autonomous Undersea Systems Institute) developed the CADCON concept [5], which employs a distributed multi-agent simulation and visualization system. In China, Fengju Kang etc. designed a semi-physical system for underwater vehicle [6].

The structure of this paper is as the following, Section II for overview of the DAUV system, the three parts control node, virtual model node and vision node of DAUV are presented in the following section III, IV and V respectively. Section VI presents the experiments comparison results between the AUV and the DAUV. Finally the conclusion is drawn in section VII.

II. OVERVIEW OF THE SYSTEM

The DAUV system developed is a semi physical virtual reality system platform. Its hardware and software are described as the following subsection.

As stated above, the virtual model node calculates the posture of AUV according to its dynamic model. The outputs of the model are the acceleration, velocity and position vectors for virtual sensors using. The vision node computes the range measured by the sonar using the position vector. The hardware interface of the control node is the counterpart of the virtual model node. That is to say, the ADC(anology digital converter) of the control node is corresponding to the DAC(digital anology converter) of the virtual model node, vice versa. One’s serial communication is corresponding to its counterpart. This is a powerful feature of this system, since the control node is always the same regardless of experiments being carried out in a real or virtual environment. The structure of the system is seen in Fig. 1.

![Fig. 1 Hardware of the System](image-url)
In this paper we present a semi-physical Virtual Reality system, which has been developed in order to aid the research for AUV. This system is composed of three nodes: control node, virtual model node and vision node. The control node is the actual control computer which running the real-time operation system QNX and the on-line or off-line planel mission, its interface have no difference between the real mode and virtual mode. The virtual node was made to realize the calculation vehicle dynamic model, navigation module, sonar module, and others sensor module etc. While the vision node is twofold, firstly, it allows the visualization of the vehicle within the ocean environment and secondly, it allows the simulation of sensors providing environment dependent information such as temperature, salinity and sonar etc.

The functions of the control node include: (1) planning the mission and tasks according to the command; (2) controlling the posture of AUV according to the behaviors decomposed by mission or tasks; (3) reckoning its position for the purpose of navigation and (4) avoiding obstacles, as occasion requires.

The functions of the virtual node include: (1) calculating the posture according to dynamic model of the AUV; (2) receiving command from the control node and pass the all of the information to the vision node and all kinds of sensors; (3) building virtual sensors such as GPS, Doppler, sonar, TCM2, permanent magnetic motor, propeller and depth gauge, altimeter etc.

The functions of the vision node include: (1) receiving posture data of AUV calculated by virtual model node and displaying its motion swimming in the three-dimension ocean environment; (2) providing the obstacle avoidance sonar data and altitude data for virtual node; (3) creating the ocean environment such as ocean terrain, current, temperature field, salinity field etc.

This system has three modes of function: VM (virtual mode), RM (real mode) and HM (hybrid mode). VM is used in the lab while developing or just being conception. RM is used when real experiments are carried out in a real environment. HM allows experimenting in virtual environments, while observing the response of the real AUV to the virtual environment sensed by the virtual sensors. This paper presented is just the comparison between RM and HM.

III. THE CONTROL NODE

The control node is the mission planner and the controller of the AUV. It adopts three hierarchical architectures [9] in charge of controlling the vehicle during a mission: the highest mission layer, the middle task layer and the lowest execution layer. Its execution command is passed to the virtual model node through the hardware interface while its sensor information is passed from the virtual world.

The highest mission layer is used for changing mission into two kinds of information: task and path for planning. The planning results are a series of tasks, which are consequently transferred to the middle task layer. It is in charge of inserting new tasks in the plan architecture trying to minimize a cost function. The planning process takes place when the user specifies a new task or when a previously planned task fails and needs re-planning.

The middle task layer is responsible for the plan representation and controlling its execution. The control execution layer makes the actual state evolve from the beginning state to the end state through a sequence of states. For each state, the execution of the related task means create or kill a set of executable behaviors, such as constant depth diving, constant altitude diving etc.

The real-time control of the AUV is in charge of the lowest execution layer, which provides information mapping mechanisms. Each executable behavior has its own goal and can be executed independently or concurrently with the others. There are safety behaviors such as obstacle avoidance and navigation behaviors like going to one point and so on. Behaviors read input values from the virtual model node and send its results to the lower level controller.

IV. THE VIRTUAL MODEL NODE

The virtual model node operates as a circumstance for purpose of virtual all kinds of devices and sensors. The dynamical model of AUV, navigation module, sonar module, thruster module and other virtual sensors are running in this node. This node receives control command from the control node, and sends module and sensors information to the control node through the corresponding hardware interface, and sends the AUV posture information to the vision node. Main modules are realized as the following description, and other modules will not be described here.

A. Dynamic Model of the AUV

The standard submarine equations of motion developed by Gertler and Hagen and revised by Humphreys and Feldman-offer a general framework for the development of the vehicle equations of motion [10]. In these equations of motion, external forces and moments

\begin{equation}
\sum F_x = F_{\text{hydro}} + F_{\text{hydro}} + F_{\text{drag}} + F_{\text{control}}
\end{equation}

are described in terms of AUV coefficients. For example, underwater AUV axial drag:

\begin{equation}
F_d = -(1/2) \cdot \rho \cdot C_d \cdot A_f \cdot u \cdot |u|
\end{equation}

where the coefficient

\begin{equation}
C_{\text{drag}} = \frac{\partial F_d}{\partial (u \cdot |u|)} = -(1/2) \cdot \rho \cdot C_d \cdot A_f
\end{equation}

The vehicle coefficients can be derived as follows [10]:

a) Axial Drag experiment;

b) Added Mass Hydrodynamic theory from Newman and empirical formulae from Blevins;

c) Vehicle Cross flow Drag Hydrodynamic theory from Newman and empirical derived formulae from Hoerner;

d) Vehicle Body lift, Empirically derived formulae from Bottaccini, Fidler and Hoerner.

The following assumptions were made in the development of the AUV model [10]:

a) AUV is a rigid body of constant mass. In other words, the vehicle mass and mass distribution do not change during operation;
b) AUV is deeply submerged in a homogeneous, unbounded fluid. In other words, the vehicle is located far from free surface (no surface effects, i.e. No sea wave or vehicle wave-making loads), walls and bottom;

c) AUV does not experience memory effects. The simulator neglects the effects of the vehicle passing through its own wake.

Combining the equations for the vehicle rigid body dynamics with the equations for the forces and moments on the vehicle, we arrive at the combined nonlinear equations of motion for the AUV in six degrees of freedom.

Surge, or translation along the vehicle x-axis [10]–[13]:

\[
(m - X_a)\ddot{u} + mz \ddot{q} - my \dot{r} = (X_{uy} - m)\omega q + (X_{uy} + mx_v)q^2 + (X_{uy} + m)\nu r + (X_{uy} + mx_v)r^2 \]

\[
+ X_{uy}u \sum |u| + X_{uy}v^2 + X_{uy}w^2
- my_x pq - mz_x pr + X_{prop} - (P - B)\sin \theta
\]

and other five equations can be obtained in the same way, then the hydrodynamic equation of motion of an underwater vehicle with 6 DOF can be conveniently described as follows matrix form [10]–[14]:

\[
(M_{RB} + M_A)\dot{v} + (C_{RB}(v) + C_A(v))v + D(v)v + G(\eta) = B \tau
\]

\[
\eta = J(\eta)v
\]

where \( M_{RB} \) is the inertia matrix, \( M_A \) is the added-mass matrix, \( \dot{v} \) is the acceleration vector, \( v \) is the velocity vector, \( C_{RB} \) is the rigid-body coriolis matrix, \( C_A \) is the added coriolis matrix, \( D \) is the damping matrix, \( G \) is gravity and buoyancy vector, \( \eta = [\phi \ \theta \ \psi]^T \) are the roll, pitch and yaw angle, \( B \) is the thruster configuration matrix, \( \tau \) is the control inputs vector, \( J(\eta) = \text{diag}[J_1(\eta), J_2(\eta)] \) is transform matrix from body coordinate system to earth coordinate system, where \( s(\cdot) = \sin(\cdot), c(\cdot) = \cos(\cdot) \).

\[
J_1(\eta) = \begin{bmatrix}
c \psi \phi & -s \psi \phi & c \psi \phi & c \psi \phi & s \psi \phi & c \psi \phi \\
c \phi \theta & -s \phi \theta & c \phi \theta & c \phi \theta & s \phi \theta & c \phi \theta \\
-s \phi \psi & c \phi \psi & s \phi \psi & c \phi \psi & -c \phi \psi & s \phi \psi \\
-s \theta & c \theta \sin \phi & -s \theta & c \theta \sin \phi & c \theta \phi & s \theta \cos \phi
\end{bmatrix}
\]

\[
J_2(\eta) = \begin{bmatrix}
1 & \sin \phi \tan \theta & \cos \phi \tan \theta \\
0 & \cos \phi & -\sin \phi \\
0 & \sin \phi / \cos \phi & \cos \phi / \cos \phi
\end{bmatrix}
\]

B. Navigation Module
The navigation devices of this system are composed of ADL (acoustics Doppler log), GPS and gyro. Several experiments were conducted for each of these sensors allowing us to compute the mean and the standard deviation of the absolute error. Here, each virtual sensor (including navigation and other module sensors) was implemented using the corresponding output of the dynamic model of AUV adding a random error signal with the corresponding mean and variance, according to the sensors’ specification. The signal can be realized by (4.7):

\[
x = \mu + \sigma * \left( \sum_{i=0}^{n-1} \text{random}_i - \frac{n}{2} \right) \quad (4.7)
\]

where: \( \mu \) denotes the mean value, \( \sigma \) denotes the standard variance, \( \text{random}_i \) denotes the random value of average distribution, \( n \) denotes an integer.

C. Sonar Module
As far as sonar concerned, only the obstacle avoidance sonar (OAS) has been implemented. Sonar can be simulated at different levels. From the physical point of view, we can use the sonar equation. Each transducer can be considered as a sound source, and taking into account the transmission losses (spreading and attenuation), we can compute the sound level in the position where the beam impacts with the surrounding objects. Each of these points of impact can then be considered a new sound source and we can compute the way back in order to compute the sound level of the reading at the receptor. When this sound level is higher than a threshold, we consider its corresponding time of flight in order to compute the range. With this kind of simulation, important effects like the multi-path can be taken into account. The drawback is the computation time. Since we are interested in simulating sonar behavior in real-time, such a method is unaffordable.

The second approach is soft calculation. Each sonar beam is simulated as a cone with degrees of aperture [2][9], which is composed of a range of intersect lines with specified distance. While the AUV moves in the virtual ocean environment, the points belonging to the cone are explored in order to see if they impact with objects in its surroundings. In this case, the axial distance plus a normal distribution error are considered as the measurement given by the transducer.

D. Thruster Module
The devices of this module are composed of DC motor and propeller. It is difficult to calculate the accuracy state of AUV, so we must consider the thrust deduction and other factors. The thrust of the propeller can be written as the following [13][15]:

\[
T = (1 - t)K_p n^2 D^4
\]

where \( t \) is thrust deduction, \( K_p \) is thrust coefficient, \( \rho \) is density of seawater(kg/m^3), \( n \) is rotate speed (rev/s), \( D \) is diameter of propeller (m), \( T \) is actual thrust (N).

According to the distribution of propellers on the AUV, the thrust and the torque, which serviced as the input of the dynamic model of the AUV, can be obtained.

E. Other Virtual Sensors Module
Concerning the sensors, we can consider two different types. First, for the sake of human safety, AUV has many sensors that monitor the danger, such as leak detection, pressure gauge and motor current detection. Second, for the
purpose of investigation, thermometer, salinity sensor, depth
gauge and altimeter are installed. These virtual sensors are
realized the same as navigation module.

V. THE VISION NODE

The vision node allows for monitoring the posture of the
AUV as well as sending sonar sensor information to the
virtual model node through a TCP/IP LAN (10/100 Mbs
adaptive Ethernet). This node has not only the function of
providing the visualization of the AUV within the ocean
environment but also allows the simulation of sensors
providing environment dependent information such as depth,
altitude, obstacle, temperature, sanity, current etc.

A. Virtual Ocean Environment

In actual, the ocean environment is very miscellaneous;
moreover it is changing at any moment. For convenience,
we only consider its temperature, salinity, current and
obstacle.

For the temperature and salinity, we build a huge body,
the temperature and the salinity data of this body store in a
database according to the statistical data. For current, lots
of grids are made; the current of in the same grid can be looked
as the same both in direction and magnitude. While for the
obstacle, many typical obstacles are made for the purpose of
validating the planned mission. When the system is running,
the obstacle can be positioned to place anywhere from
model library.

1) Current implement method

The motion of ocean current is very complex as a matter
of fact, since the effects of the ocean circumfluence, surface
air circumfluence, typhoons, and density etc [16][17],
further more; the motion of underwater vehicle will affect its
surrounding current. So the actual situation is: the law of
the magnitude and the direction of the current somewhere in the
determinate ocean terrain are the function of its position and
time: underwater vehicle swims in the current somewhere,
and its motion affect the motion of surrounding current, later,
underwater vehicle continues to swim in the mixed current,
and current continue to affect the motion of vehicle, and so
on. But the relationship between vehicle and current can not
resolve in real time at present, and the level of computer
calculate and hydrodynamics need make further more progress.

The motion of current not only affects the posture of
underwater vehicle, but also its temperature, salinity and
other factors affect the sensors installed on the vehicle. If the
motion of current is directional in the ocean, the conductor
of this current may result in large error of sensors on vehicle
[18]. Two kinds of methods were adopted in the digital
UUV platform as the following:

a) Current database

In order to implement the motion of current, database
need built based on the history statistical current data. Since
the magnitude and direction exist large differences in the
surface layer, middle layer and bottom layer, only the data
of middle layer current are stored in the database. The
horizontal current of XOY plane can be obtained by the
method of bi-variate interpolation based on grid data. Assume the n*m coordinates in the XOY plane is:

\[ x_0 < x_1 < \cdots < x_{n-1} \]
\[ y_0 < y_1 < \cdots < y_{m-1} \]

and their corresponding current values are:

\[ z_q = z(x_i, y_j) \]  

where \( i = 0,1, \ldots, n-1 \), \( j = 0,1, \ldots, m-1 \), the approximation
value in the point \((u, v)\) can be obtained by (4.12):

\[ z(x, y) = \sum_{i=0}^{n-1} \sum_{j=0}^{m-1} \left( \prod_{k=0}^{n} \frac{x-x_k}{x_i-x_k} \right) \left( \prod_{l=0}^{m} \frac{y-y_l}{y_j-y_l} \right) z_q \]

And the method in the vertical direction adopts
piecewise linear approximation according to history
statistical current data. In this way, the current of any point
in the ocean can be implemented. The method of
temperature and the salinity of the ocean are implemented in
the same way.

The method above is appropriate for in possession of
mass data of the ocean current. If current data of region
concerned cannot be obtained, two methods can be used,
one is experiential, and the other is as the following.

b) Hydrodynamics software calculation

This method is based on the hydrodynamics theory and
numerical analysis. After the models of ocean terrain and
typical obstacles are built, they are imported into the
hydrodynamics calculation software, such as CFX etc. Once
the boundary condition and the data necessary are inputted
into the software, the ocean current in any position can be
calculated in this way. The value calculated using the
method above is very close to real condition, so this method
is widely used in the research work of underwater vehicle.

2) Benthos terrain

Some terrain conversion algorithms [17][19] for
development of the benthos terrain, such as nearest neighbor
interpolation, linear interpolation, cubic interpolation and
v4- interpolation are compared; Secondly, a new terrain
conversion algorithm for development of the benthos terrain
DTTCGSFD (Delaunay Triangle-based Terrain Considering
of Grid, Sparse, Feature Data) is introduced. This method
consider the data not only distance constant grid data, sparse
data, but also feature data with the terrain data, such as
fathom line etc.

B. Display Module

The display system displays three part contents: (1) real
time display the position of AUV within 3D virtual ocean
environment, (2) display the condition of all the devices and
sensors information and (3) display the data stored in the
black box.

The execution of the experiments in virtual mode before
executing the real experiments allows us to detect and solve
development problems in the laboratory before going to the
trial environment.

Some results have been obtained are the following (see
fig. 3).
Fig. 3 Ocean terrain for experiment

Figure 3 shows the posture and the altitude of AUV in current position. The beams around it stand for the range and the angle of obstacle detect sonar, which can detect the distance of the obstacle using sonar installed in difference directions. The object, viewpoint, channel, sea color and bottom effect etc. can be setting during the virtual mode or hybrid mode. Since the ocean environment is hazard, and it may be result in huge lose. So in order to verify the performance of the control node, some random obstacle can be placed in the ocean environment during a mission execution.

VI. EXPERIMENT RESULTS

Before the lake experiment is conducted, the same mission planned is pre-executed on the semi physical digital AUV platform. The Comparison result between the lake experiment’s results and digital AUV platforms are showed as the heading control in the horizontal plane and the depth control in the vertical plane.

A. Heading Control

For heading step response, the following mission is designed for test in the DAUV before AUV test in the lake:

GALS(10*60, 230, 2, Depth_Mode, 3);
GALS(8*60, 50, 2, Depth_Mode, 3);

The first parameter of function GALS is the gale time; the following is the expected heading, speed, gale mode and expected depth respectively. Accordingly, AUV moves at the speed of 2 knots at depth 3 meters, the heading step made the step from 2300 to 500, its step response results can be shown as the following figure.

B. Depth Control

While for depth step response, the following mission is designed for test in the DAUV before AUV test in the lake either:

POSITION(3*60, 50, 0, Depth_Mode, 3);
POSITION(2*60, 50, 0, Depth_Mode, 8);

The first parameter of function POSITION is the gale time; the following is the expected heading, speed, gale mode and expected depth respectively. Accordingly, AUV moves at the speed of 0 knots at heading 50 degree, the depth step made the step from 3 to 8 meters, its step response results can be shown as the following figure.

C. Performance comparison

The stable performance and dynamic performance comparison results between DAUC and AUV are shown as the following table1 and table 2 respectively.

<table>
<thead>
<tr>
<th>Platform</th>
<th>RMS</th>
<th>Max error</th>
<th>Min error</th>
</tr>
</thead>
<tbody>
<tr>
<td>DAUV</td>
<td>0.081</td>
<td>0.219</td>
<td>-0.234</td>
</tr>
<tr>
<td>AUV</td>
<td>0.27</td>
<td>0.72</td>
<td>-0.78</td>
</tr>
</tbody>
</table>

Table 2 dynamic performance comparisons

<table>
<thead>
<tr>
<th>Platform</th>
<th>Overshot</th>
<th>Raise time</th>
<th>Stable time</th>
</tr>
</thead>
<tbody>
<tr>
<td>DAUV</td>
<td>0%</td>
<td>10s</td>
<td>56s</td>
</tr>
<tr>
<td>AUV</td>
<td>1.9%</td>
<td>10s</td>
<td>26s</td>
</tr>
</tbody>
</table>

VII. CONCLUSION

Comparison the lake experiment’s results with digital AUV platform’s showed that: (1) the horizontal controller parameters worked perfectly well while they were applied in the actual AUV; (2) the vertical controller parameter didn’t work as well as the horizontal plane, and the dynamic model
of AUV on the spot need to be improved greatly later, because there exist much more difference between the actual AUV and virtual one, and (3) the stable and dynamic performance almost are the same between the virtual and real experiments.

The further work will include the following: (1) the further research on the dynamic model of the AUV, (2) the algorithm of controller designing, and (3) building a distributed underwater vehicle simulation platform for the cooperation work purpose.

REFERENCE