The design method research of the control system for Autonomous Underwater Vehicle (AUV) using Linear Matrix Inequality (LMI)

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Abstract: An Independent Administrative Corporation Japan Agency for Marine-Earth Science and Technology (JAMSTEC) is developing light-and-small Autonomous Underwater Vehicles (AUV)[1], named 'MR-X1' (Marine Robot Experimental 1), which can cruise, investigate and observe by itself without human's help. In this paper, we consider the motion control problem of 'MR-X1' and derive a controller. Since the dynamic property of 'MR-X1' is changed by the influence of the speed, the mathematical model of 'MR-X1' becomes the nonlinear model. In order to design a controller for 'MR-X1', we generally apply nonlinear control theories or linear control theories with some constant speed situation. If we design a controller by applying Linear Quadratic (LQ) optimal control theory, the obtained controller only compensates the optimality at the designed speed situation, and does not compensate the stability at another speed situations. This paper proposes a controller design method using Linear Matrix Inequalities (LMIs)[2,3,4], which can adapt the speed variation of 'MR-X1'. And examples of numerical analysis using our designed controller are shown.

Keywords: Autonomous Underwater Vehicle (AUV), MR-X1 (Marine Robot Experimental 1), Linear Quadratic (LQ) optimal control, Linear Matrix Inequality (LMI), Equation of motion

1. INTRODUCTION

Although 70 percents on the surface of the Earth is the ocean, a lot of unexplored parts have been left. In these days, efficient investigations of the ocean and the seabed have been interested. However, undersea is the extreme environment that we can't step into easily. Therefore operating robots for taking over from human being is desired. If such kind of robots had been developed, we can avoid danger.

In order to realize it, an Independent Administrative Corporation Japan Agency for Marine-Earth Science and Technology (JAMSTEC) is developing light-and-small Autonomous Underwater Vehicles (AUV) to explore the ocean. The AUV named 'MR-X1' (Marine Robot Experimental 1) can cruise, investigate and observe by itself without human's help. In order to be able to turn in a small space and explore efficiently, 'MR-X1' has five thrusters. One main thruster is for the forward and the backward motion, two thrusters are for the horizontal motion and two thrusters are for the vertical motion.

In this paper, the motion control problem of this AUV 'MR-X1' is considered. In order to operate 'MR-X1', five thrusters have to be controlled appropriately. Since two vertical thrusters set up by inclining from the perpendicular, if these vertical thrusters are rotated, 'MR-X1' not only moves the vertical direction but also moves the horizontal direction. In the case of considering the cruising 'MR-X1' with the constant altitude, both vertical and horizontal thrusters have to be controlled appropriately. The present paper considers that 'MR-X1' is controlled to make it go straight on surge direction, and stop at the targeting point with the constant altitude.

Since the dynamic property of 'MR-X1' is changed by the influence of the speed, the mathematical model of 'MR-X1' becomes the nonlinear model. In order to design a controller for 'MR-X1', we generally apply nonlinear control theories or linear control theories with some constant speed situation. If the controller is designed by applying the Linear Quadratic

(LQ) optimal control theory, the obtained controller only compensates the optimality at the designed speed situation, and does not compensate the stability at another speed situations. In order to solve this problem, this paper proposes a controller design method using Linear Matrix Inequalities (LMIs), which can adapt the speed variation of 'MR-X1'. By applying this method, we will be able to find suitable gain on the speed variation of 'MR-X1'. And examples of numerical analysis using our designed controller are shown.

Fig.1 Autonomous Underwater Vehicle 'MR-X1'

Table 1 Principal specification of 'MR-X1'

Dimensions	2.5[m](total length) × 0.8[m](width) × 1.2[m](height)
Weight	800[kg] (in the air)
Cruising Speed	2[kt]
Maximum Depth	4200[m]
Actuators	1. Main thruster (400W) 2. Two horizontal thrusters (150W) 3. Two vertical thrusters (150W)

2. EQUATION OF MOTION FOR 'MR-X1'

2.1 Coordinate system

In this paper, we use two coordinate systems. One is the Earth-fixed coordinate system and the other is the Body-fixed coordinate system. Fig.2 shows the relation between each coordinate system. In general, linear and angular velocities are represented by using Body-fixed coordinate system, but the translation to the Earth-fixed coordinate system is suitable to observe the motion of 'MR-X1'. The matrix of coordinate transformation between the Earth-fixed coordinate system and the Body-fixed coordinate system becomes as follow.
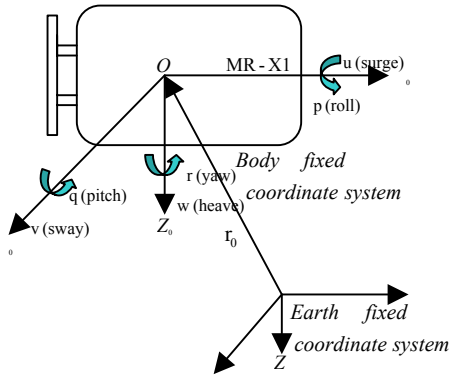
Fig.2 Coordinate system of 'MR-X1'

$$\dot{\eta} = J(\eta)\nu \qquad (2.1)$$

$\eta = [x, z, \vartheta, y, \phi, \varphi]^T$ Position and angle vector with the Earth-fixed coordinate system

$\nu = [u, w, q, v, p, r]^T$ Linear and angular velocity vector with the Body-fixed coordinate system

x, y, z Position
ϕ, ϑ, φ Angle
u, v, w Linear velocity
p, q, r Angular velocity

$$J(\eta) = \begin{bmatrix} \cos\varphi\cos\vartheta & \sin\varphi\sin\phi + \cos\varphi\cos\phi\sin\vartheta & 0 \\ -\sin\vartheta & \cos\vartheta\cos\phi & 0 \\ 0 & 0 & \cos\phi \\ \sin\varphi\cos\vartheta & -\cos\varphi\sin\phi + \sin\vartheta\sin\varphi\cos\phi & 0 \\ 0 & 0 & \sin\phi\tan\vartheta \\ 0 & 0 & \sin\phi/\cos\vartheta \end{bmatrix}$$

$$\begin{matrix} -\sin\varphi\cos\phi + \cos\varphi\sin\vartheta\sin\phi & 0 & 0 \\ \cos\vartheta\sin\phi & 0 & 0 \\ 0 & 0 & -\sin\phi \\ \cos\varphi\cos\phi + \sin\phi\sin\vartheta\sin\varphi & 0 & 0 \\ 0 & 1 & \cos\phi\tan\vartheta \\ 0 & 0 & \cos\phi/\cos\vartheta \end{matrix} \qquad (2.2)$$

$J(\eta)$ Velocity transformation matrix

2.2 Dynamics of 'MR-X1'

The motion of underwater vehicle is represented as the 6DOF nonlinear equation[5]. In general, its motion can be treated as the motion of Rigid-body. The nonlinear equation is represented as

$$M\dot{\nu} + C(\nu)\nu + D(\nu)\nu + g(\eta) = \tau \qquad (2.3)$$

M Inertial Matrix
C(ν) Matrix of Coriolis and Centripetal Terms
D(ν) Damping Matrix
g(η) Matrix of Restoring Forces and Moments Thrusts

2.2.1 Inertial Matrix

Inertial matrix is defined as the sum of inertial mass matrix M_{RB} and added inertial matrix M_A due to the inertia of the surrounding fluid.

$$M \equiv M_{RB} + M_A \qquad (2.4)$$

$$M_{RB} = \begin{bmatrix} m & 0 & mz_G & 0 & 0 & 0 \\ 0 & m & -mx_G & 0 & 0 & 0 \\ mz_G & -mx_G & I_{yy} & 0 & 0 & 0 \\ 0 & 0 & 0 & m & -mz_G & mx_G \\ 0 & 0 & 0 & -mz_G & I_{xx} & 0 \\ 0 & 0 & 0 & mx_G & 0 & I_{zz} \end{bmatrix} \qquad (2.5)$$

$$M_A \equiv -\begin{bmatrix} A_{11} & 0 & 0 & 0 & 0 & 0 \\ 0 & A_{33} & 0 & 0 & 0 & 0 \\ 0 & 0 & A_{55} & 0 & 0 & 0 \\ 0 & 0 & 0 & A_{22} & 0 & 0 \\ 0 & 0 & 0 & 0 & A_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & A_{66} \end{bmatrix} \qquad (2.6)$$

Position of the center of gravity of 'MR-X1' can be represented as $[x_G, 0, z_G]^T$ with the Body-fixed coordinate system. It is assumed that the product of inertia I_{**} is 0, because 'MR-X1' has the symmetrical configuration. Furthermore, the added mass A_{**} is also 0 except diagonal elements.

2.2.2 Matrix of Coriolis and Centripetal Terms

The matrix of coriolis and centripetal terms is defined as the sum of the coriolis matrix of Rigid-body $C_{RB}(\nu)$ and the coriolis matrix in ideal fluid $C_A(\nu)$.

$$C(\nu) \equiv C_{RB}(\nu) + C_A(\nu) \qquad (2.7)$$

$$C_{RB} = \begin{bmatrix} 0 & 0 & -m(x_G q - w) \\ 0 & 0 & -m(z_G q + u) \\ m(x_G q - w) & m(z_G q + u) & 0 \\ 0 & 0 & m(z_G r + x_G p) \\ -mz_G r & m(z_G p - v) & I_{zz} r \\ m(x_G r + v) & -mx_G p & -I_{xx} p \end{bmatrix}$$

$$\begin{matrix} 0 & mz_G r & -m(x_G r + v) \\ 0 & -m(z_G p - v) & m(x_G p + y_G q) \\ -m(z_G r + x_G p) & -I_{zz} r & I_{xx} p \\ 0 & -mw & mu \\ mw & 0 & -I_{yy} q \\ -mu & I_{yy} q & 0 \end{matrix} \qquad (2.8)$$

$$C_A = \begin{bmatrix} 0 & 0 & -A_{33}w & 0 & 0 & A_{22}v \\ 0 & 0 & A_{11}u & 0 & -A_{22}v & 0 \\ A_{33}w & -A_{11}u & 0 & 0 & A_{66}r & -A_{44}p \\ 0 & 0 & 0 & 0 & A_{33}w & -A_{11}u \\ 0 & A_{22}v & -A_{66}r & -A_{33}w & 0 & A_{55}q \\ -A_{22}v & 0 & A_{44}p & A_{11}u & -A_{55}q & 0 \end{bmatrix} \qquad (2.9)$$

2.2.3 Damping Matrix

The damping matrix of 'MR-X1' in the fluid is represented as

$$D(v) = -diag\{X_u, Z_w, M_q, Y_v, K_p, N_r\}$$
$$-diag\{X_{u|u|}|u|, Z_{w|w|}|w|, M_{q|q|}|q|, Y_{v|v|}|v|, K_{p|p|}|p|, N_{r|r|}|r|\}$$

$$= -\begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & Z_w & Z_q & 0 & 0 & 0 \\ 0 & M_w & M_q & 0 & 0 & 0 \\ 0 & 0 & 0 & Y_v & 0 & Y_r \\ 0 & 0 & 0 & K_v & 0 & K_r \\ 0 & 0 & 0 & N_v & 0 & N_r \end{bmatrix}$$

$$-\begin{bmatrix} X_{uu}|u| & X_{ww}|w| & 0 & X_{vv}|v| & 0 & 0 \\ 0 & Z_{ww}|w|+Z_{wq}|q| & Z_{qq}|q| & 0 & 0 & 0 \\ 0 & M_{ww}|w|+M_{wq}|q| & M_{qq}|q| & 0 & 0 & 0 \\ 0 & 0 & 0 & Y_{vv}|v|+Y_{vr}|r| & 0 & Y_{rr}|r| \\ 0 & 0 & 0 & 0 & K_{pp}|p| & 0 \\ 0 & 0 & 0 & N_{vv}|v|+N_{vr}|r| & 0 & N_{rr}|r| \end{bmatrix} \quad (2.10)$$

The first term is the force and the moment of the first order of the velocity, and the second term is the second order of the velocity. These values of the matrix components are obtained from experiments.

2.2.4 Restoring Forces and Moments

The position of the force of buoyancy of 'MR-X1' can be represented as $[x_B, 0, z_B]^T$ with the Body-fixed coordinate system, so the restoring forces and moments are represented as

$$g(\eta) = \begin{bmatrix} (W-B)\sin\theta \\ -(W-B)\cos\theta\cos\phi \\ (z_G W - z_B B)\sin\theta + (x_G W - x_B B)\cos\theta\cos\phi \\ -(W-B)\cos\theta\sin\phi \\ (z_G W - z_B B)\cos\theta\sin\phi \\ -(x_G W - x_B B)\cos\theta\sin\phi \end{bmatrix} \quad (2.11)$$

where

W　Force of gravity,　　B　Force of buoyancy

2.2.5 Thrusts

In this paper, the following expression is used as the mathematical model of thrusts of 'MR-X1'. These components are the function of the rotational speed of thrusters.

$$\tau = \begin{bmatrix} X_{THM} \\ Z_{TVL}\cos\alpha + Z_{TVR}\cos\alpha \\ -|z_{THM}|\cdot X_{THM} + |x_{TVL}|\cdot Z_{TVL}\cos\alpha + |x_{TVR}|\cdot Z_{TVR}\cos\alpha \\ -Y_{THF} - Y_{THR} - Z_{TVL}\sin\alpha + Z_{TVR}\sin\alpha \\ -|z_{THF}|\cdot Y_{THF} + |z_{THR}|\cdot Y_{THR} - |z_{TVL}|\cdot Z_{TVL}\sin\alpha \\ -|y_{TVL}|\cdot Z_{TVL}\cos\alpha + |z_{TVR}|\cdot Z_{TVR}\sin\alpha + |y_{TVR}|\cdot Z_{TVR}\cos\alpha \\ -|x_{THF}|\cdot Y_{THF} + |x_{THR}|\cdot Y_{THR} + |x_{TVL}|\cdot Z_{TVL}\sin\alpha - |x_{TVR}|\cdot Z_{TVR}\sin\alpha \end{bmatrix} \quad (2.12)$$

X_{THM}　Thrust of the main thruster

Y_{THF}　Thrust of the front horizontal thruster

Y_{THR}　Thrust of the rear horizontal thruster

Z_{TVL}　Thrust of the portside vertical thruster

Z_{TVR}　Thrust of the starboard vertical thruster

$[x_{THF}, y_{THF}, z_{THF}]$　Position of the front horizontal thruster

$[x_{THR}, y_{THR}, z_{THR}]$　Position of the rear horizontal thruster

$[x_{TVL}, y_{TVL}, z_{TVL}]$　Position of the portside vertical thruster

$[x_{TVR}, y_{TVR}, z_{TVR}]$　Position of the starboard vertical thruster

where

$$X_{THM} = \rho n_{THM} |n_{THM}| D_{THM}{}^4 K_T \quad (2.13)$$
$$Y_{THF} = 0.84628 n_{THF} + 0.01724 n_{THF}{}^2 + 0.0155 n_{THF}{}^3 \quad (2.14)$$
$$Y_{THR} = 0.98582 n_{THR} + 0.02722 n_{THR}{}^2 + 0.01577 n_{THR}{}^3 \quad (2.15)$$
$$Z_{TVL} = 0.95576 n_{TVL} + 0.02028 n_{TVL}{}^2 + 0.01512 n_{TVL}{}^3 \quad (2.16)$$
$$Z_{TVR} = 0.96669 n_{TVR} + 0.02204 n_{TVR}{}^2 + 0.01526 n_{TVR}{}^3 \quad (2.17)$$

n_{THM}　Rotational speed of the main thruster

n_{THF}　Rotational speed of the front horizontal thruster

n_{THR}　Rotational speed of the rear horizontal thruster

n_{TVL}　Rotational speed of the portside vertical thruster

n_{TVR}　Rotational speed of the starboard vertical thruster

α　Declination of vertical thrusters [rad]

$D_{THM} = 0.48$　Diameter of the main thruster [m]

$K_T = 0.171$　Thrust coefficient

$\rho = 1025$　Fluid density [kg/m^3]

These thrusters have following limitations.

$$-5 \leq n_{THM} \leq 5, \qquad -12 \leq n_{THF}, n_{THR}, n_{TVL}, n_{TVR} \leq 12$$

3. DESIGNING A CONTROL SYSTEM FOR 'MR-X1'

The aim of developing 'MR-X1' is to construct the autonomous underwater vehicle that it not only follows the given path but also stops at the objective point and keeps the point to investigate, observe and operate. In order to realize these, five thrusters equipped on 'MR-X1' have to be controlled to be appropriate rotational speeds. In order to know the dynamic characteristic of 'MR-X1', the main thruster was only rotated firstly. Since the displacement toward to the heave direction occurred, to keep constant altitude, two vertical thrusters have to be rotated. However, vertical thrusters set up by heaving the inclination from the perpendicular. If these thrusters are rotated, 'MR-X1' not only moves the vertical direction but also changes the horizontal direction. Therefore, in the case of cruising 'MR-X1' with the constant altitude, these five thrusters have to be controlled appropriately. The present paper considers the controller design problem for 'MR-X1' to make it go straight on surge direction, and stop at the objective point with the constant altitude. It is obvious that this mechanical model of 'MR-X1' depends on the speed of each direction; surge, sway and heave. In order to design a controller, we have to consider effects of these speed variations. However, in our problem, the main thruster is used the different way compared with other thrusters; the main thruster is used for the straight cruising toward the surge direction with speed u, and other thrusters are used for holding attitude or following the path. This means that if other thrusters are controlled appropriately from the start, variations of speeds for vertical and horizontal directions can be controlled to become variation sufficiently small and we need not to consider effects of variations of speeds. Therefore, in this paper, we design a control system to adopt the variation of the speed for the surge direction.

3.1 Linearization

In order to design a control system, we divide the mechanical model 'MR-X1' into surge motion part and the others and linearize the other part of the mechanical model except the surge direction speed u. The speed u is used as a parameter. Furthermore, the pitch angle and the pitch rate are

neglected, because the control of the pitch angle is difficult from the constitutional character of 'MR-X1'. The linearized model is shown as follows.

Matrix of coordinate transformation

$$J(\eta) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3.1}$$

Inertial matrix

$$M_L = \begin{bmatrix} m - A_{33} & 0 & 0 & 0 \\ 0 & m - A_{22} & -mz_G & mx_G \\ 0 & -mz_G & I_{xx} - A_{44} & 0 \\ 0 & mx_G & 0 & I_{zz} - A_{66} \end{bmatrix} \tag{3.2}$$

Matrix of coriolis and centripetal terms

$$C_L(v) = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & (m - A_{11})u \\ 0 & 0 & 0 & 0 \\ 0 & -(m - A_{11})u & 0 & 0 \end{bmatrix} \tag{3.3}$$

Damping matrix

$$D_L(v) = -\begin{bmatrix} Z_w & 0 & 0 & 0 \\ 0 & Y_v & 0 & Y_r \\ 0 & K_v & 0 & K_r \\ 0 & N_v & 0 & N_r \end{bmatrix} \tag{3.4}$$

Matrix of restoring forces and moments

$$g_L(\eta_L) = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & z_G W - z_B B & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \tag{3.5}$$

State variable

$$x = [\eta_L, v_L]^T \tag{3.6}$$

where

$$\eta_L = [Z, Y, \phi, \varphi], \qquad v_L = [w, v, p, r]$$

Thrusts

$$\tau_L = \begin{bmatrix} 0 & 0 & \cos\alpha & \cos\alpha \\ -1 & -1 & -\sin\alpha & \sin\alpha \\ -|z_{THF}| & |z_{THR}| & -|z_{TVL}|\sin\alpha - |y_{TVL}|\cos\alpha & |z_{TVR}|\sin\alpha + |y_{TVR}|\cos\alpha \\ -|x_{THF}| & |x_{THR}| & |x_{TVL}|\sin\alpha & -|x_{TVR}|\sin\alpha \end{bmatrix} \bullet$$
$$\begin{bmatrix} 0.84628 & 0 & 0 & 0 \\ 0 & 0.98582 & 0 & 0 \\ 0 & 0 & 0.95576 & 0 \\ 0 & 0 & 0 & 0.96669 \end{bmatrix} \tag{3.7}$$

3.2 State Equation

The state equation of 'MR-X1' is represented as

$$\dot{x} = A(u)x + B\bar{\tau} \tag{3.8}$$

$$x = [\eta_L, v_L]^T = [Z, Y, \phi, \varphi, w, v, p, r]^T$$
$$\dot{x} = [\dot{\eta}_L, \dot{v}_L]^T = [\dot{Z}, \dot{Y}, \dot{\phi}, \dot{\varphi}, \dot{w}, \dot{v}, \dot{p}, \dot{r}]^T \quad \text{State variable}$$
$$\bar{\tau} = [n_{THF}, n_{THR}, n_{TVL}, n_{TVR}]^T \quad \text{Input}$$

$$A = \begin{bmatrix} -M_L^{-1}\{C_L(u) + D_L\} & -M_L^{-1}g_L(\eta_L) \\ J_L(\eta_L) & 0_{4\times 4} \end{bmatrix} \tag{3.9}$$

$$B = \begin{bmatrix} M_L^{-1}\bar{\tau} \\ 0_{4\times 4} \end{bmatrix} \tag{3.10}$$

3.3 Designing a control system

In this section, the control system is designed to control 'MR-X1' moving toward the objective point. The control system is firstly designed using the linear quadric (LQ) optimal control. Generally, in order to design the LQ optimal control system for linear systems, it is necessary to solve the Algebraic Riccati equation by using constant matrices A and B in the state equation. Since the Riccati equation is solved easily by using some computer softwares, the state feedback control system can be easily obtained. In order to apply the LQ control theory for 'MR-X1', we have to fix the cruising speed u. Therefore, the optimality of the obtained control system is only compensated about the one speed. However, the obtained control system does not compensate the stability in other speed situations.

In order to compensate the stability, we propose the new design method by using the LMI, which correspond to the Riccati inequality. The algorithm to solve the LMI has a property that can solve some number of LMIs simultaneously. By applying this property, it is considered that we can obtain the solution that satisfies the LMI condition under several speeds. The proposed strategy to design the control system is represented as follow.

The LMI that corresponds to Riccati equation in LQ optimal control on state equation (3.8) is represented as

$$\begin{bmatrix} A(u_i)X + XA(u_i)^T - BB^T & XC^T \\ CX & -I \end{bmatrix} < 0 \qquad (i = 0, \ldots, m) \tag{3.11}$$

$$X > 0$$

The constant matrix C corresponds to the weighting matrix in LQ optimal control. The speed parameter u including LMI is given appropriately. By applying the algorithm to solve the LMIs, we can obtain one solution X. In this case, the control input $\bar{\tau}$ is represented as

$$\bar{\tau} = -B^T X^{-1} x \tag{3.12}$$

Note that the solution X satisfies LMI conditions on all speed parameters. This means that the obtained control system compensates the stability for all speed situations, which substitute for parameters u.

4. SIMULATIONS

4.1 Simulation conditions

Table 2 Requirements of simulations

Simulation time	600[sec]
Initial position	[-30.0(m), 1.0(m), 1.0(m)]
Target point	[0(m), 0(m), 0(m)]

For LQ optimal control systems, two types of simulations were done. One is the optimal gain for the surge speed 0[m/s] (Case 1), and the other is for 0.3[m/s] (Case 2). The speed of 0[m/s] corresponds to keeping the objective point. The speed 0.3[m/s] is the middle speed of 'MR-X1' since the maximum speed of 'MR-X1' is about 0.6[m/s]. On the other hand, for LMIs, we simulated using the controller that derived by substituting speed parameters between 0[m/s] and 0.7[m/s] (Case 3).

4.2 Simulation results

Case 1

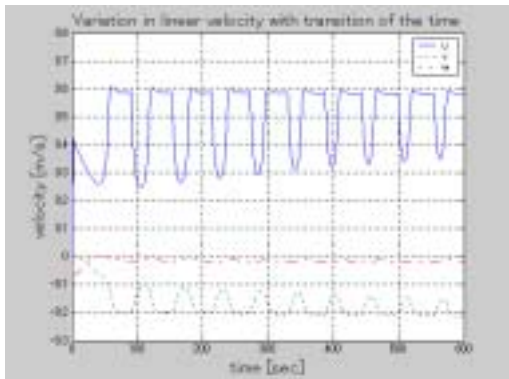
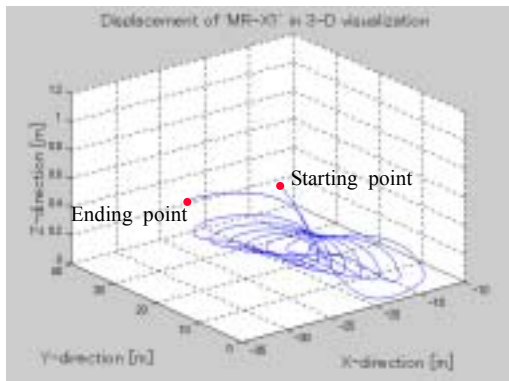Fig.3   Variation in linear velocity with transition of the time

Fig.4   Displacement of 'MR-X1' in   D visualization

The movement from the initial position to the objective point occurs the velocity consequently, so the control system of 0[m/s] cannot compensate the stability at the speed occurring, and 'MR-X1' tends to diverge like Fig.3 and Fig.4.
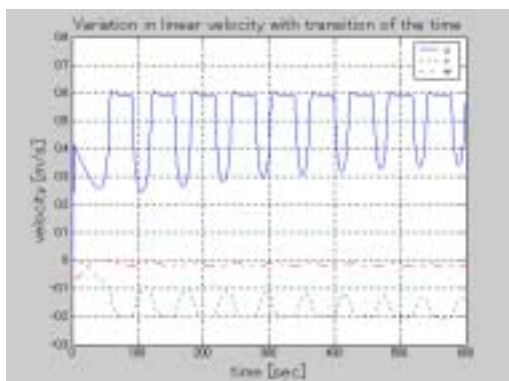
Case 2

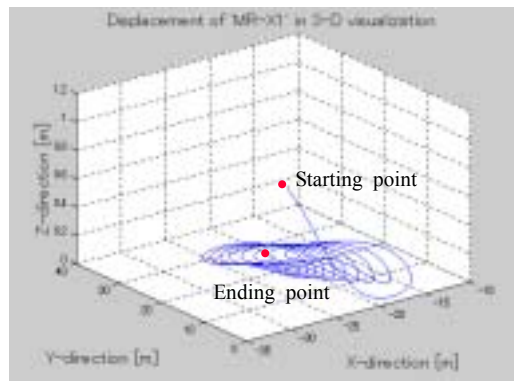Fig.5   Variation in linear velocity with transition of the time

Fig.6   Displacement of 'MR-X1' in   D visualization

The 'MR-X1' does not always cruise with the constant speed. Therefore, when speed changing occurs, the optimal gain will fluctuate in each case, and if we use the control system that derived under one fixed speed like this simulation, the obtained control system cannot compensate the stability at other speed situations, 'MR-X1' tends to diverge like Fig.5 and Fig.6.
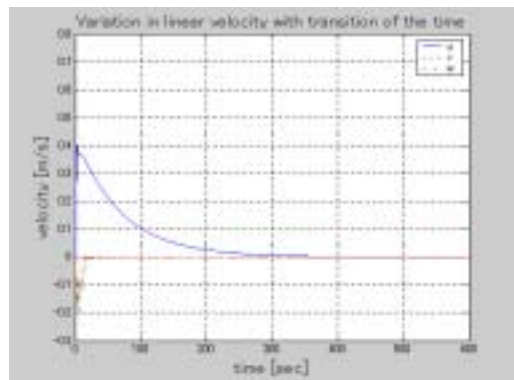
Case 3

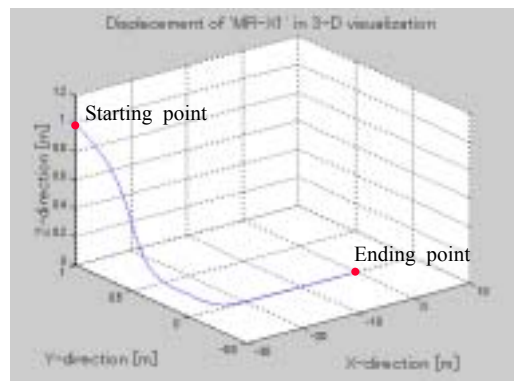Fig.7   Variation in linear velocity with transition of the time

Fig.8   Displacement of 'MR-X1' in   D visualization

Initial deflections of Y-axis and Z-axis converge to the desired path on X-axis. The speed of 'MR-X1' is reduced and becomes 0[m/s] at the origin.

5. CONCLUSIONS

In this paper, the mathematical model of Autonomous Underwater Vehicle named 'MR-X1', which is developing at JAMSTEC, was derived. We set the aim on autonomous tracking given path and stopping at the objective point, and for this aim, we applied LQ optimal control system and LMIs. In the result, LMIs made it possible to design a control system that corresponds to speed changing, and showed the robustness. It has more effective performance than LQ optimal control system.

Now, this development is in the stage of performance test. We are going to confirm this simulation results with sea-trial of 'MR-X1'.

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