# Control System Design for Docking Actuator

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## Abstract

This paper presents a research on the control system design for actuators used in the docking system in space.

The motion of docking system is considered to have three phases, i.e. approach, matching and attenuation phases. In the approach phase, relative velocity, attitude and alignment are controlled to obtain suitable docking interface. In this paper, control strategies for the matching and the attenuation phases after the approach are considered.

In the matching phase, the actuator is accelerated to match the velocity of the approaching target. A design of feedback control is shown for this phase, making use of Kalman filter to obtain target speed estimation from the -relative distance observation.

In the attenuation phase, the actuator is decelerated to attenuate the kinetic energy of the target. The most effective *way* of attenuation is considered to be the constant acceleration attenuation.--In-this paper a control method is presented to attain this type of attenuation. Another method is applied to design compliance control strategy which adjust the actuator force for different kinetic energy of the docking target.

A laboratory prototype of electromechanical docking actuator is developed in order to show validity of the control system and to compare theoretical and experimental performances.

## Introduction

The docking system is one of the most important functions for the space station and the orbiter such as space shuttle. Recently the construction of many large scale space stations is planned. Many kinds 6f docking/berthing system must be required for space construction, assembly and servicing.

A soft docking system is considered to consist of a laser docking sensor system to obtain position and attitude of the approaching target, a mechanical docking interface system which provides the easy adjustment of the docking interface and rigid coupling of two docking vehicles, an electromechanical actuator system which adjust the docking interface in order to eliminate misalignments, to minimize contact forces and to reduce disturbances caused by the docking, and a docking computer system which processes the sensor data to obtain control signal required for the accurate adjustment of alignment and the effective force attenuation.

The docking between the station and the orbiter is the low-speed docking where the final approach speed is ultimately slow. Precise control of velocity and alignment is performed during the approach phase to minimize contact and stroking forces. On the other hand, the high-speed docking system will be utilized for docking between objects such as small conveyer vehicles, robots, construction equipments, etc. where the docking with rather high speed is inevitable and force attenuation is more significant. In the latter case, the docking actuator is desired to make `hard' docking as `soft' as possible.

The--development of the docking system needs variably controlleel=actuators for energy absorption, compliance control and adjustment of a docking interface to eliminate misalignments.

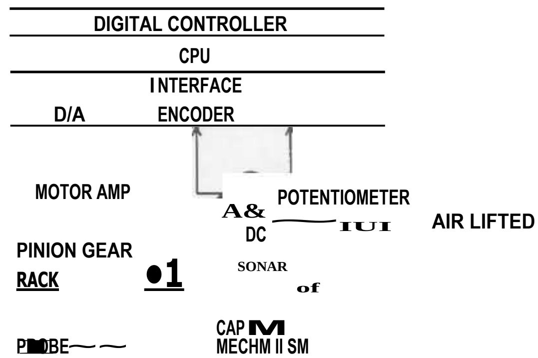


Figure 1: Experimental docking system

The use of an electromechanical actuator is considered to be most suitable for docking system in space.

Basic researches concerning the docking / berthing system are presented by Burns et al [1], Stokes et al [5] etc.. Fundamental approaches for the control of docking systems are shown in Niwa et al [6] [7]. In this paper further investigations are presented about the control of docking actuator for the matching and attenuation phases.

## Experimental Docking System

A laboratory prototype of electromechanical docking actuator system is developed in order to analyze the attenuation characteristics and to develop a design method of control system for docking actuator.

The configuration of experimental system consists of a rack-and-pinion gear actuator, a servo motor, sensors, a digital controller and a air-lifted docking target. Its block diagram is shown in Fig.1.

Many experimental docking systems recently developed use the roller screw or ball screw mechanism for actuators. However a rack-and-pinion gear actuator is utilized in the present system for the simplicity of structure and high response speed.

This docking system makes use of a sonar ranging system as a substitute for the laser range sensor which will be used for rea docking systems in space environment. In this system only the target body is lifted by air and can move in one direction along the channel with the least friction. This system is controlled by a digital control system which includes a microcomputer, interfaces and an amplifier for sensors and actuators.

## Phases of Docking Motion

The motion of docking system is considered to have three phases i.e. approach, matching and attenuation phases. Especially con-

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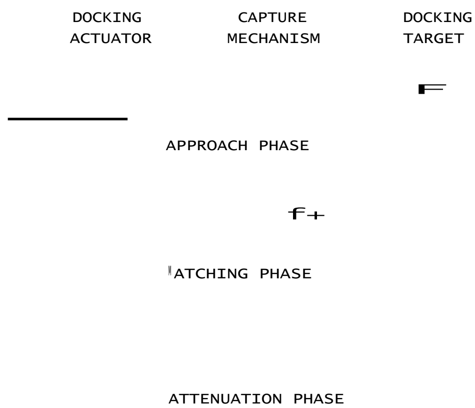



Figure *2:* Three phases of docking motion

siderations concerning control system for the matching and attenuation phases are presented in this paper.

Approach phase In the beginning of the docking motion, control effort is devoted to adjust relative velocity, attitude and alignment to obtain suitable docking interface of both target and capture vehicles. This phase is called `approach phase' in this paper.

There axe many significant problems concerning sensor configuration and information processing as well as control problems for attitude, position and velocity of both vehicles.

Matching phase Before the contact between the docking vehicles begins, the relative velocity between them should be minimized for the smooth docking. We call this stage `matching phase'.

In matching phase, the actuator is accelerated to match the velocity of the approaching target. If the actuator has enough acceleration ability and response speed, the relative velocity can be reduced to the vicinity of zero after a certain amount of time. However the relative velocity must be controlled to become zero at just-the same point that they come into contact. In fact strictly simultaneous matching is impossible in a finite duration of time, as far as the linear feedback control law is used. However it is shown that practically the amount of mismatching can be made small enough by applying a suitable integral compensation.

Attenuation phase When the docking vehicles come close enough or touch each other after the matching phase, the capture mechanism of docking system begins to work and is rigidly coupled with the target vehicle. After this, the actuator is decelerated to attenuate the kinetic energy of the target. When the docking target vehicle stops its relative motion perfectly, whole docking process come to end. We call this stage `attenuation phase'.

## Control System for Docking Actuator

Basic concept and design methods of control system for electromechanical docking actuator will be shown here.

Docking actuator The most important functions of the electromechanical actuator is considered to be the following items.

- Piovide precise position and velocity control for alignment of docking interface.
- Absorb the relative kinetic energy due to the final approach velocity.
- Control docking force to adjust compliance for the docking targets with different weights.
- Reduce the disturbance effects caused by the impact of the docking especially for the frequency band of structural mode of flexible appendices.

In order to provide above functions, docking actuators should have both attenuation and actuation functions, allow adequate length of actuation stroke and change attenuation performance characteristics in real time in accordance with the kinetic energy of the target.

A control system design for the matching phase and for the attenuation control scheme are investigated and the experimenta results will be shown in this paper.

Control for matching phase In this phase the actuator is controlled to match the position and the velocity with the target. Simultaneous matching of velocity and position should be attained here. Control scheme for this phase is designed by considering the desired settling time which is specified by actuator stroke length and target's approach speed. Designed control system includes Kalman filter to obtain target speed estimation from the relative distance observation. An integral type compensation is effective to reduce the matching error at contact point.

Constant acceleration attenuation During the absorption of the relative kinetic energy both target and the docking system accept force ( or acceleration ). One of the best scheme of attenuation is to minimize the maximum force. According to this scheme, acceleration should be constant during the attenuation.

In order to practice this attenuation scheme, actuator should be controlled to move with constant acceleration.

Control for compliance adjustment Each docking target vehicle has different relative kinetic energy ( mass and velocity ). As the actuator stroke is limited, the compliance of attenuator should be adaptively adjusted for each target. The relative velocity can be sensed by using a laser sensing device. Real-time sensing of the mass of the target vehicle and adaptive compliance adjustment is possible during the initial stage of the attenuation process.

## Design of Control System

In this section a design of the control system for the experimenta docking system are presented. The control for the matching phase and the attenuation phase are presented.

Model of the docking system Simplified model of the experimental docking system is shown in Fig.3. Equations of motion for the docking system with a DC servo motor, a rack-pinion gear and a capture mechanism are given by

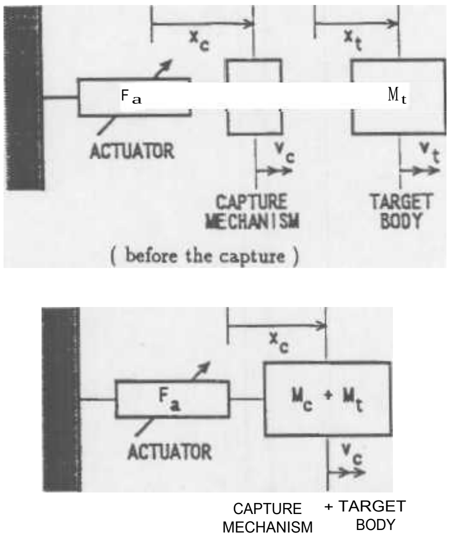
$$V = R.I+K\sim.(i,/r), \qquad (1)$$

$$J \cdot \underset{r}{z} = Kt \cdot I-D_{,,r}, \qquad (2)$$

The motor amp is voltage controlled type and its characteristics is given by

$$V = K, V, \qquad (3)$$

where symbols are defined as follows.




( after the capture )

Figure 3: A model of the docking system

- • motor amp input voltage.
- • armature input voltage.
- I armature current.
- R armature resistance.
- r radius of pinion gear.
- • motor amp gain.
- • back electromotive-force constant.
- • motor torque constant.
- D, load constant.
- • inertia of actuator.
- $M_M$ equivalent mass of actuator.
- M, mass of target body.
- z~ position of capture mechanism.
- v, velocity of capture mechanism.
- x, position of target body.
- v, velocity of target body.
- z, distance x, - z,.
- v, relative velocity v, - $v_c$.

The transfer function G(s) from amp input voltage $V$, to $x$, is given by the following equation.

$$G(s) = V = s^2 + 'ais \tag{4}$$

where the constants al and $b_i$ are given by

$$a_i = \frac{K,K,}{JR} + \frac{D,}{J,} \quad b_i = \frac{K,K,r}{JR} \tag{5}$$

Setting.x, = (x, i.)' and u = $V$. , the following state equation is obtained from above equation.

$$\dot{x}_c = A_c x_c + B_c u$$

$$( 0 \; -a_i ) x, + ( b_i ) u, \tag{6}$$

We assume that motion of the target body is a constant velocity linear motion without any external force after approach phase. Therefore the equation of motion for the target body during the matching phase before the.capture is given by the following equation.

$$\dot{v}_t = 0 \tag{7}$$

Combining the motion of the docking system and the target body, the state space equation of whole system is obtained as follows. Using distance x, = z, - z,, and relative velocity v, = v, - v., we set state and control vector as $x_d$ = (z,, v, x, v,)' and u = V,. Then the state equation of whole system is given as

$$\dot{x}_d = A_d x_d + B_d u$$

$$\begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & a_i & 0 & 0 \end{bmatrix} x_d + \begin{bmatrix} 0 \\ 0 \\ 0 \\ -b_i \end{bmatrix} u. \tag{8}$$

In the configuration of the feedback control system for the experimental docking system, position and velocity of capture mechanism x, and v. are measured by potentiometer and optical en. coder. The range between the capture mechanism and the target z, = x, - x~is measured by a sonar attached near the capture mechanism.

Setting a measurement vector $y = (x_5$ v, z,)' , observation equation is given as

$$y = C_d x_d = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} x_d \tag{9}$$

The relative velocity between them v, = v, - v. is not included in 3 dimensional measurement vector but is estimated from the sonar data assuming that the velocity of the target does not change before the capture. These four variables can be used for the composition of feedback signal.

After the capture, the capture mechanism and the target body are rigidly coupled. Then the motion is described by the same equation as (6) with changing $J$ to J, = $J + M_t r^2$ ( M. to $M_t = M_c + M_t$).

Control for matching phase In this phase the actuator is controlled to match the position and the velocity with the target. Distance and relative velocity between the capture mechanism and the target body should be reduced to zero simultaneously.

Because the target is assumed to have a constant velocity in matching phase, this control can be achieved by composing a simple second order system, which is obtained by using a feedback law

$$u = k1z, + k2v, + (ar/bi)v,, \tag{10}$$

$$k_i = w'./b_i, \quad k_2 = 2t;w,/b_i,$$

where ( and w,, are damping coefficient and natural frequency which will be assigned later.

The purpose of the control is to make the velocity of docking probe v, reach 2 % vicinity of the target velocity v,.

Design procedure is as follows. First the stroke length of matching phase $s_m$ is specified which should be decided considering whole stroke length s,, and the attenuation stroke s, s,, = s, + s, ). From the matching stroke length and the relative target velocity we can obtain the settling time of the system in which the relative velocity and the distance reach in the specified ( 2 %a) vicinity of zero. Desired system can be composed which satisfies the specified settling time.

( = 1 is chosen in order that the system response has no overshoot. Then the settling time T. when v, reaches within the 2 % vicinity of v, satisfies the following equation.

$$w,T, = 5.834 \tag{11}$$

If the-initial value of distance is $x_r(0) = d_o$, we obtain

$$T_r v_t = d_o + \qquad (12)$$

When $\zeta = 1$, the velocity of the docking probe $v_r(t)$ is given by

$$v_r(t) = v_t\{1 - e^{-w_n t}(1 + W t)\}. \qquad (13)$$

then the matching stroke length $s_m$ is expressed as

$$s_m = \int_0 v_r(t)dt = v_t\{T_r - (2/w_n)(1 - e^{-s.ea4})\}$$

$$= 0.6282 T_r v_t = 0.6582(4 + 3_m) \qquad (14)$$

From this, the following key equation is obtained

$$d_o = 0.51933_m. \qquad (15)$$

If the matching phase is initiated when the distance satisfies $x_r(t) = d_o$, the velocity matching is achieved with $x_r(t) = 0$ simultaneously.

Kalman filter to obtain relative velocity An ultrasonic range sensor is utilized to obtain distance from an edge of docking probe to the docking target in our experimental docking system. Any device is not used to measure the relative velocity between the docking probe and the target. The relative velocity signal is obtained from the distance signal.

Here Kalman filter technique is applied to get an estimation of relative velocity between the docking probe and the target. First we assume system and measurement noise in the state space system equation (8) and the observation equation (9). We obtain new system and observation equation as

$$\dot{x}_d = A_d x_d + B_d u + \xi, \qquad (16)$$

$$y = C_d x_d + \eta, \qquad (17)$$

where $\xi(t)$ and $\eta(t)$ are uncorrelated zero mean white Gaussian noise and their covariance matrices are given by

$$E[\xi(t)\xi(\tau)^T] = W\delta(t - \tau), \quad E[\eta(t)\eta(\tau)^T] = V\delta(t - \tau), \qquad (18)$$

where $W > 0$ and $V > 0$. Kalman filter gain $L$ is given by

$$L = P C_d V^{-1} \qquad (19)$$

where P is the unique positive definite solution of the following Riccati equation.

$$P A_d + A_d P - P C_d V^{-1} C_d P + W = 0 \qquad (20)$$

Using the above Kalman filter gain L, Kalman filter equation which produces $\hat{x}$, the estimated value of $x_d$ is given by

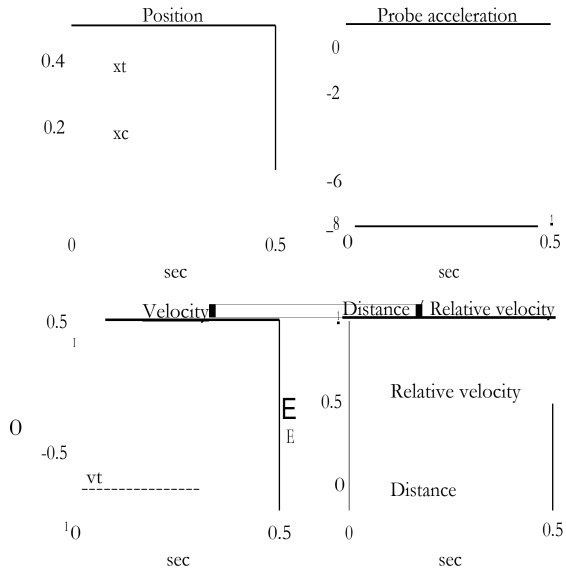
$$\dot{\hat{x}}_d = (A_d - L C_d)\hat{x}_d + (L \quad B_d) \binom{y}{u}$$

Here noise covariance intensity matrices W and V are assumed as

$$W = 1000 \cdot \text{diag}(1, 1, 1, 1000), \qquad V = 13. \qquad (22)$$

and Kalman filter gain is calculated as

$$L = \begin{bmatrix} 3.16e+1 & 4.43e-3 & 1.56e-4 \\ 4.43e-1 & 2.81e+1 & 6.69e-3 \\ 1.56e-4 & 6.69e-3 & 1.45e+2 \\ 2.37e-2 & 1.18e+0 & 1.00e+4 \end{bmatrix} \qquad (23)$$




Initial condition : $z_t = 0.38$ (m), $v_t = -0.8$ (m/s), $z_r = 0.3$ (m) $v_r = 0.0$ (m/s)
Matching stroke length : 0.15 (m)

Figure 4: A simulation of the matching phase

Addition of integral compensator The actuator stroke for the matching phase is limited so the matching should be completed in rather short period which is decided by the stroke length and the approaching velocity of the target. In practical situations steady state matching error after a limited matching period is inevitable. Matching error results in a hard contact of docking objects. Therefore reduction of steady state matching error is the most important purpose of the control strategy for matching phase. Addition of integral compensation is an effective method to improve the steady state performance of the control system. In fact this modification of the control loop has greatly improved the steady state matching error and remarkably reduced the shock induced by small mismatching.

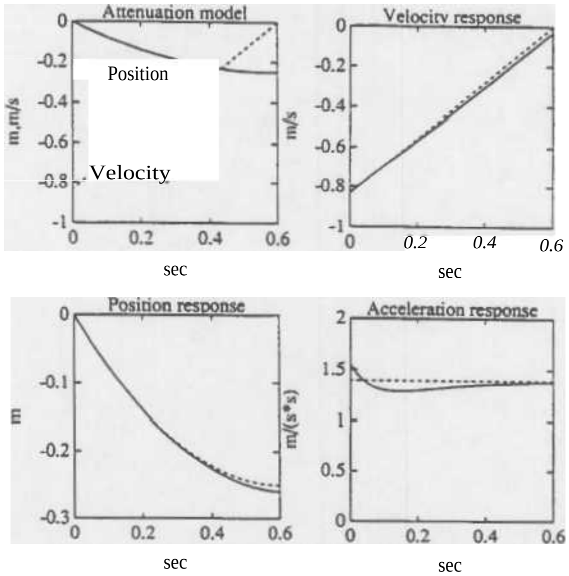
Simulation of matching phase A simulation of matching phase motion is shown in Fig.4. The distance and the relative velocity between the target and capture mechanism are reduced to zero almost at the same time. Simultaneous matching of velocity and position is achieved.

Control for constant acceleration attenuation Attenuation should be completed within the specified actuator stroke length $s_r$. The magnitude of constant acceleration is decided by the target velocity $v_t$ and the stroke length $s_r$. At the capture point the velocity of the target $v_t$ and that of docking probe $v_r$ coincides and the magnitude of them are known by the control computer. The magnitude of acceleration $a_r$ and the curves of velocity and position, $v_r(t)$ and $z_r(t)$, for ideal attenuation model can be calculated from $v_t$ and $s_r$ by the following equations.

$$a_r = v_t^2/(2s_r), \; v_r(t) = v_t + a_r t, \; x_r(t) = x_r(0) + v_t t + (1/2)a_r t^2. \qquad (24)$$

This ideal attenuation ends at time $t_r = -v_t/a_r$ where $v_r(t) = 0$ is attained.

A control strategy for the constant acceleration attenuation is designed to make the system response follow this ideal model. A




Initial condition : s, = 0.0 (m), v, = -0.83 (m/s)
Attenuation stroke length : *0.25 (m)*

Ffgure 5: A simulation of constant acceleration attenuation

feedback control input to achieve this purpose is given by

$$u = k_r(z_r - z.) + k_2(v_r - v_A) \tag{25}$$

where the feedback gains $k_r$ and $k_z$ are designed by ordinary design method such as linear quadratic regulator. By this control the docking actuator performs approximate constant acceleration attenuation. A simulation of constant acceleration attenuation is shown in Fig.5, where the solid lines show the system response and the broken lines show the model response.

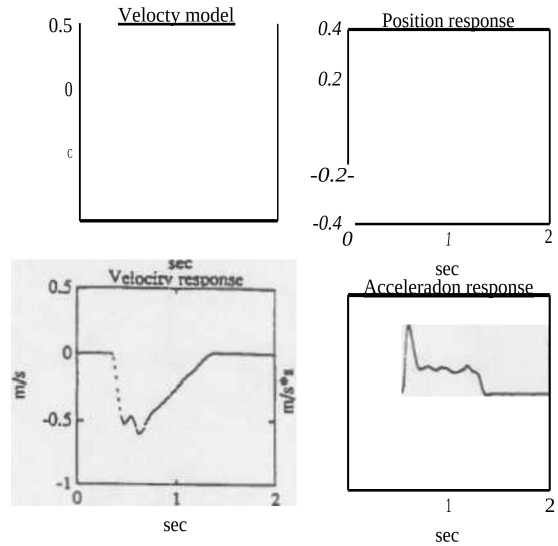
Compliance adjustment control In this control scheme the actuator force is adjusted according to the kinetic energy of the target. At the initial stage of the attenuation, the control input is set to zero in order that the actuator force is kept minimum ( only the friction force and the back electromotive force ). The estimation of the target's kinetic energy is performed in this stage using the equation $\Delta F = M.\Delta v$. where $\Delta F$ denotes the total force applied during this stage and $\Delta v$, is the variation of the velocity. After this estimation stage constant force is applied for attenuation. If the constant attenuator force and stroke length of attenuation are given by $F$ and $s_a$, the total work is expressed by $F \cdot s_a$. From the fact that the total work equals to the kinetic energy of the mass $M$. with a velocity v , we obtain $(1/2)M_t v^2 = F s_a$. From this equation the control input for the constant force attenuation is given by the following equation.

$$U = M^{eb'}_{t} + 6, i\sim \tag{26}$$

## Experimental Results

The results of docking experiment using the. developed system are shown in Fig. 6, 7, 8, and 9.

The results of experiment using constant acceleration attenuation for cases with different target velocity and weight are shown in Fig. 6 and 7, where the velocity model and the system responses are depicted. Acceleration signals are obtained from accelerometers which is attached to the target body.




Constant acceleration attenuation
Target velocity : 0.819 (m/s)
Target weight : 0.734 (Kg)

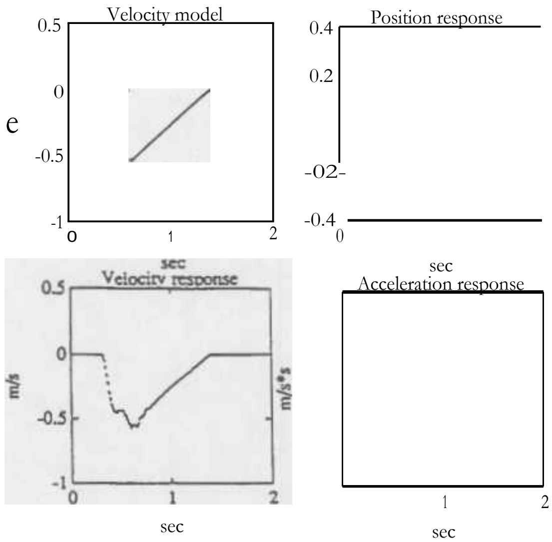
Figure *6:* Experimental Result I

From these figures it is known that almost constant acceleration is achieved. One important point which distinguish experimental result from theoretical one is that experimental curves include peaks and/or vibrational motions just after the moment of capture. This phenomena results from the fact that very smal mismatching of velocity is unavoidable at the capture point because of the linear feedback control scheme during the matching phase, and that the elasticity of capture mechanism produces vibrational motion at the beginning and the end of attenuation. For the precision docking which is robust for the variation of docking condition, velocity mismatching should be reduced as small as possible. Therefore this is an important problem to be solved.

The results of docking experiment for the compliance adjustment attenuation scheme are shown in Fig. 8 and 9 for cases with different target velocity and weight. In this case actuator force is hold minimum at the beginning of attenuation so that the acceleration peak caused by the velocity mismatching is much lower than the constant acceleration case.

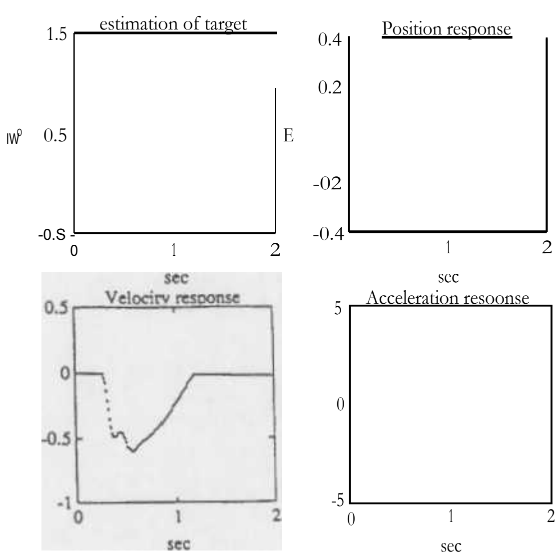
## Conclusion

A design method of control system is presented for the docking actuators. The phase of velocity matching and that of attenuation in the soft docking process are investigated by utilizing an experimental docking test facility which includes an electromechanical actuator and an air-lifted docking target. Experimenta research with rather high-speed docking situation revealed fundamental characteristics of docking motion. Fully adaptive compliance control of docking actuator is next subject of our research.



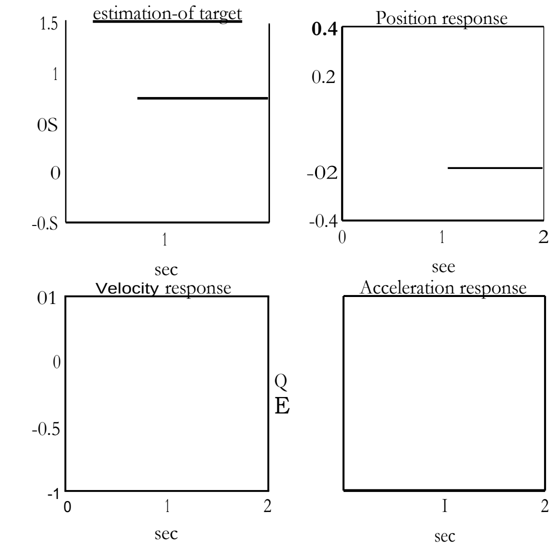

Constant acceleration attenuation
Target velocity : 0.767 (m/s)
Target weight : 1.201 (Kg)

Figure 7: Experimental Result II




Compliance adjustment attenuation
Target velocity : 0.697 (m/s)
Target weight : 1.201 (Kg)

Figure 8: Experimental Result III




Compliance adjustment attenuation
Target velocity : 0.715 (m/s)
Target weight : 0.734 (Kg)

Figure 9: Experimental Result IV

## Acknowledgement

This work was supported by the Ministry of Education, Science and Culture of Japan under Grant in Aid for Scientific Research No.01460161.

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