Transactions on the Built Environment vol 19, © 1996 WIT Press, www.witpress.com, ISSN 1743-3509

TugRobot satellites for in-orbit servicing

S. Matsunaga, Y. Fukushima, H. Yamamoto, Y. Ohkami
Department of Mechano-Aerospace Engineering, Tokyo Institute of Technology, 2-12-1 O-okayama, Meguro-ku, Tokyo 152, Japan

Abstract

In this paper, we propose a TugRobot Satellite, which is a space-robot for transporting materials or satellites, as a kind of in-orbit servicing satellite. The principal concept and technical issues of the TugRobot Satellite are discussed, and particular emphasis is placed on the notion of "pushing an object," which is the fundamental function involved in transporting objects. This paper deals mainly with two problems: estimation and transportation. The first is the problem of in-orbit estimation of mass properties which are often completely unknown or exhibit uncertainties to some extent. The second is the motion problem, including rotation, translation, and orbit transfer for supporting operations using only impulsive thruster forces. To show the viability of the investigated methods for resolving the above mentioned problems, results of numerical simulations of mass property estimation and translation/rotation coupled control are presented. We conclude that it is possible for the TugRobot Satellite to transport an object from one arbitrary place to another using estimated mass properties and thrusters attached at any point on the transported object.

1 Introduction

It is expected that because more large structures will be constructed in orbit, there will be an increasing need for service-satellites to support in-orbit activities. In-orbit service satellites tend to have complex mechanisms to perform sophisticated functions, and this results in large cost and long development time. To reduce the complexity of service satellites, the authors propose a simple service satellite which offers fundamental functions such as pushing an object in a desired direction with no *a priori* information about the satellite.

Figure 1 illustrates the concept of a *TugRobot satellite*. The remaining discussion is divided into two parts. The first part discusses techniques for estimat-

Transactions on the Built Environment vol 19, © 1996 WIT Press, www.witpress.com, ISSN 1743-3509

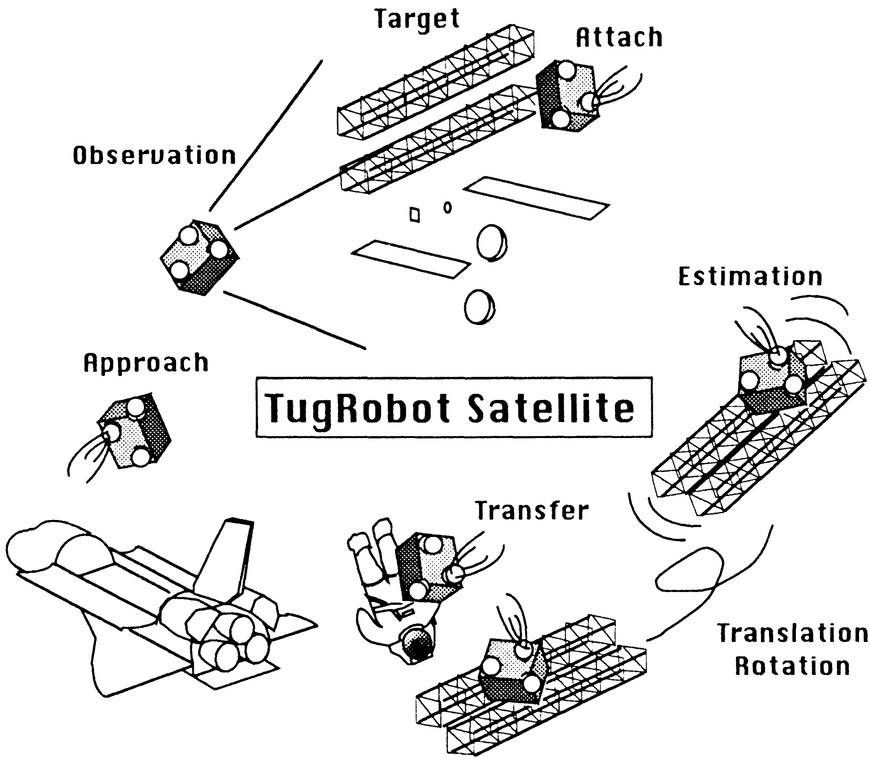


Figure 1: Concept of TugRobot satellites.

ing the physical properties of the target. Although mass properties of the structures are calculated and measured before launch, there still remain uncertainties about the object once it is in orbit. Moreover, in some case the mass properties itself change because of shape deformation, docking with other objects, or separation during in-space assembly. Therefore, estimation of the mass properties of the composite materials is necessary, especially considering transportation by means of robots or satellites. This estimation technique can be applied during recovery of damaged satellites.

The second part of the study concerns the transporting problem. Thrusters are needed for transporting materials in orbit, but it is almost impossible to attach thrusters to appropriate places of an unknown object, and thus it is necessary to develop a way to control the translational and rotational coupling motion of a satellite using thrusters attached at locations restricted by the shape of the satellite.

As a proof-of-concept study of TugRobot Satellites, this report discusses both estimation of mass properties which are totally unknown or uncertain to some extent, and the analysis of motions, such as rotation, translation, and orbit transfer, for in-orbit support operations with impulsive thruster forces.

Transactions on the Built Environment vol 19, © 1996 WIT Press, www.witpress.com, ISSN 1743-3509

2 Dynamic Analysis of TugRobot Satellites

2.1 Concept of TugRobot Satellite

The TugRobot Satellite which we are proposing here is a kind of space-robot for supporting orbital operations such as transporting materials, recovering deformed satellites in orbit, or deorbiting space debris as illustrated in figure 1. The name TugRobot is derived from the concept of "Tug Boats," which offer a similar service to boats or other materials stranded along a river. The TugRobot Satellite functions as follows. First, it attaches itself to space materials or deformed satellites (hereafter referred to as *Material Satellites*) either independently or assisted by astronauts. The mass properties of the Material Satellite are estimated from the response of the target to translational and rotational motions induced by firing of the TugRobot Satellite's thrusters. After it is deemed possible to control the Material Satellite based on the estimated parameters, the TugRobot Satellite then transports the Material Satellite to the desired location. The transport distance can range between several meters to several kilometers, and during the motion the Material Satellite is controlled in both position and attitude.

This paper presents a dynamic analysis of a repositioning maneuver using a TugRobot satellite. Details regarding how the TugRobot Satellite clings to the Material Satellite will be reported in forthcoming papers. Figure 2 outlines the procedure and indicates the relevant issues during each stage of the maneuver.

2.2 Estimation of Mass Properties

The Extended Kalman Filter method is used to estimate the mass properties, assuming that both the Material Satellite and TugRobot Satellite are rigid and that

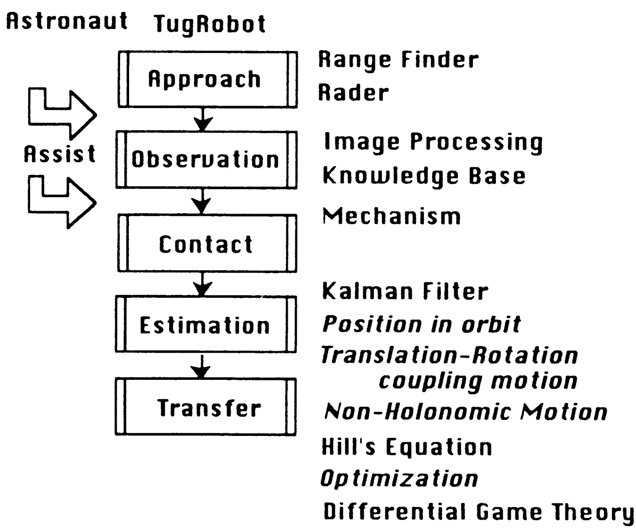


Figure 2: Repositioning maneuver and relevant issues.

Transactions on the Built Environment vol 19, © 1996 WIT Press, www.witpress.com, ISSN 1743-3509

they are connected rigidly. These two connected bodies are hereafter referred to collectively as *the Combined Satellite*. Estimating the mass properties requires analyzing the dynamic response against known dynamic inputs. These inputs are the translational and rotational motions induced by operation of the TugRobot Satellite thrusters. The dynamic response, consisting of angular velocities, attitude angles, and location of the Satellite, is measured with a rate gyro, an earth magnetic sensor, and a GPS receiver that are mounted on the TugRobot Satellite. The estimated values are the mass, the location of the center of mass, the orientation of the principal axis of inertia, and the moments of inertia of the Target Satellite.

Figure 3 depicts the coordinate systems used in the dynamic analysis of TugRobot satellite. The following equations represent the mathematical model of this estimating system. Notations are adopted with their usual meanings.

TugRobot Satellite

mass: m

center of mass: $\boldsymbol{x}_t = \{i\}^{\mathrm{T}} x_t$

moments of inertia: $\boldsymbol{I}_{to} = \{b\}^{\mathrm{T}} I_{t0}\{b\} = \{b\}^{\mathrm{T}} diag(I_{t01} \quad I_{t02} \quad I_{t03})\{b\}$

quaternions: $q = [q_1, q_2, q_3, q_4]^{\mathrm{T}} \quad (q_1^2 + q_2^2 + q_3^2 + q_4^2 = 1)$

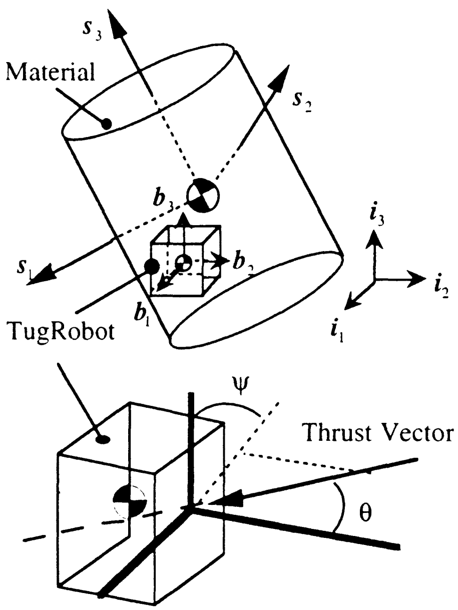


Figure 3: Coordinate system definition.

Material Satellite

mass: M

center of mass: $\boldsymbol{x}_s = \{i\}^{\mathrm{T}} x_s$

moments of inertia: $\boldsymbol{I}_{s0} = \{s\}^T I_{s0}\{s\} = \{s\}^T diag(I_{s01}, I_{s02}, I_{s03})\{s\}$

quaternions: $Q = [Q_1, Q_2, Q_3, Q_4]^{\mathrm{T}} \quad (Q_1^2 + Q_2^2 + Q_3^2 + Q_4^2 = 1)$

Direction Cosine Matrices:

$$C = \begin{bmatrix} q_1^2 - q_2^2 - q_3^2 + q_4^2 & 2(q_1q_2 + q_3q_4) & 2(q_1q_3 - q_2q_4) \\ 2(q_1q_2 - q_3q_4) & -q_1^2 + q_2^2 - q_3^2 + q_4^2 & 2(q_1q_4 + q_2q_3) \\ 2(q_1q_3 + q_2q_4) & 2(-q_1q_4 + q_2q_3) & -q_1^2 - q_2^2 + q_3^2 + q_4^2 \end{bmatrix}$$

$$D = \begin{bmatrix} Q_1^2 - Q_2^2 - Q_3^2 + Q_4^2 & 2(Q_1Q_2 + Q_3Q_4) & 2(Q_1Q_3 - Q_2Q_4) \\ 2(Q_1Q_2 - Q_3Q_4) & -Q_1^2 + Q_2^2 - Q_3^2 + Q_4^2 & 2(Q_1Q_4 + Q_2Q_3) \\ 2(Q_1Q_3 + Q_2Q_4) & 2(-Q_1Q_4 + Q_2Q_3) & -Q_1^2 - Q_2^2 + Q_3^2 + Q_4^2 \end{bmatrix}$$

Equations of motion:

$$\dot{x} = v$$

$$\dot{v} = \frac{1}{m + M} C^{\mathrm{T}} F$$

$$\dot{q} = \frac{1}{2} \begin{bmatrix} q_4 & -q_3 & q_2 & q_1 \\ q_3 & q_4 & -q_1 & q_2 \\ -q_2 & q_1 & q_4 & q_3 \\ -q_1 & -q_2 & -q_3 & q_4 \end{bmatrix} \begin{bmatrix} \omega_1 \\ \omega_2 \\ \omega_3 \\ 0 \end{bmatrix}$$

$$\dot{\omega} = I\left[T - \left(\tilde{\omega} I + \dot{I}\right)\omega\right]$$

Combined Satellite

center of mass : $x = x_t + \dfrac{M}{M + m} C^T X_s$

resultant torque: $T = \left(X_f - \dfrac{M}{M + m} X_s \right)^{\sim} F$

Transactions on the Built Environment vol 19, © 1996 WIT Press, www.witpress.com, ISSN 1743-3509

moments of inertia: $I_t = I_{t0} + m\left[y_t^T y_t U - y_t y_t^T\right]$

$$y_t = x_t - x = -\frac{M}{M+m} X_s$$

$$I_s = D^T I_{s0} D + m\left[y_s^T y_s U - y_s y_s^T\right]$$

$$y_s = x_s - x = \frac{m}{M+m} X_s$$

known quantities: $I_{t0}^{3\times1},\ m,\ X_f^{3\times1}$

$$\frac{d}{dt} I_{t0}^{3\times1} = 0^{3\times1},\ \frac{d}{dt} m = 0,\ \frac{d}{dt} X_f^{3\times1} = 0^{3\times1}$$

state variables: $x^{3\times1},\ v^{3\times1},\ q^{4\times1},\ \omega^{3\times1}$

estimated quantities: $M,\ Q^{3\times1},\ X_s^{3\times1},\ I_{s0}^{3\times1}$

observation quantities: $\omega^{3\times1},\ \ddot{x}_t^{3\times1},\ q^{3\times1}$

To estimate the moment of inertia of the Combined Satellite, the following conditions must be satisfied.

$$I_2 + I_3 > I_1 \qquad I_3 + I_1 > I_2 \qquad I_1 + I_2 > I_3$$
$$I_1, I_2, I_3 > 0$$

The followings is the re-mapping of the moments of inertia.

$$\begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} = \zeta\left(x_1 + \frac{1+\xi}{2}\left(x_2 - x_1\right) + \frac{1+\xi}{2}\frac{1+\eta}{2}\left(x_3 - x_2\right)\right)$$

$$x_1 = \frac{1}{\sqrt{1+1+2^2}}\begin{bmatrix} 1 \\ 1 \\ 2 \end{bmatrix},\ x_2 = \frac{1}{\sqrt{2^2+1+1}}\begin{bmatrix} 2 \\ 1 \\ 1 \end{bmatrix},\ x_3 = \frac{1}{\sqrt{1+2^2+1}}\begin{bmatrix} 1 \\ 2 \\ 1 \end{bmatrix}$$

$$\xi = \frac{2}{\pi}\tan^{-1}\left(j_1\right), \eta = \frac{2}{\pi}\tan^{-1}\left(j_2\right), \zeta = \exp\left(j_3\right)$$

The quantities j_1, j_2, j_3 are used in the estimation instead of I_1, I_2, I_3 to maintain the physical meanings of the above equations during the estimation process.

2.3 Orbit Advance and Orbit Transfer

This section discusses a method for advancing a Target Satellite along an earth orbit using the TugRobot. Orbit advance using TugRobots has some unique properties. The orbit advance is performed with only the thrusters mounted on the TugRobot Satellite and because there is a limitation on the direction of thrust, an acrobatic-like motion may be required in order to stop at the specified position as shown in figure 4. Note that with only a pushing thruster the Combined Satellite can not be decelerated without an attitude maneuver.

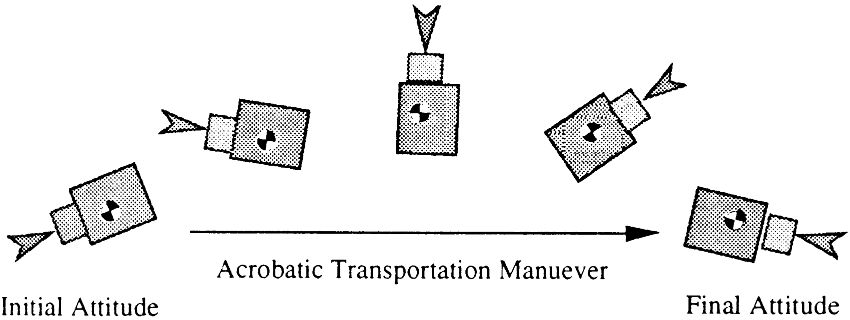


Figure 4 : An Orbit Advance using direction-limited thrusters.

In the special case of the two-dimensional problem—in which the mass and inertia distributions of the Combined Satellite are symmetrical about its rotation axis, the orbit plane is normal to the axis, and the direction of thrust can be selected to be on the orbital plane— the orbit advance problem can be solved by using an explicit analytical method with CW solutions of Hill's equations for the rendezvous problem to control the velocity of the Combined Satellite.

In the general three-dimensional case, however, the problem is more difficult because the Combined Satellite is, in general, asymmetric, and nonholonomic constrained rotational motion is used to control translational motion. Moreover, it isn't always possible to independently control the translational and rotational motion of the satellite because the direction of thrust doesn't always pass through the center of mass. One approach for solving the coupled translation/rotation maneuver problem will be discussed in a later section.

3 Numerical Simulations

3.1 Results of Mass Property Estimation

Table 1 lists the simulation parameters. The material satellite is modelled as a uniformly dense cylinder, and the TugRobot is attached to one of the curved surfaces, as depicted in figure 3. In this paper, the thruster sequence is chosen so as to maximize the induced rotational motion.

Figure 5 shows the results of simulations of estimation using mock-up data

Transactions on the Built Environment vol 19, © 1996 WIT Press, www.witpress.com, ISSN 1743-3509

Table 1: Simulation parameters.

TugRobot				
mass	30.0			[Kg]
principal moments	2.0	3.0	3.0	[Kgm2]
initial position	10.0	5.0	5.0	[m]
initial velocity	0.0	0.1	0.0	[m/s]
initial attitude angles	20.0	10.0	0.0	[deg]
initial angular velocity	0.0	0.0	0.1	[rad/s]
Material Satellite				
mass	20.0			[Kg]
principal moments	2.0	1.5	1.50	[Kgm2]
center of mass	0.5	0.0	0.0	[m]
attitude angles	0.0	0.0	0.0	[deg]

Thruster Input Sequence				
firing[S]	holding [S]	level [%]	θ [deg]	ψ [deg]
1.0	1.0	100.0	0.0	0.0
3.0	0.5	50.0	80.0	0.0
5.0	0.5	50.0	80.0	0.0
7.0	0.5	50.0	-80.0	0.0
9.0	0.5	50.0	-80.0	0.0
11.0	0.5	50.0	0.0	-45.0
13.0	0.5	50.0	0.0	45.0
15.0	0.5	50.0	45.0	45.0
19.0	0.5	50.0	-45.0	-45.0

from sensors, after forming the equations of motion of the translational and rotational motion of the Satellite. Pitch, roll, and yaw represent Euler angles which determine the relative orientation between the principal axis of inertia of the TugRobot Satelite and the attitude of the Material Satellite. X_{s1} , X_{s2}, X_{s3} are components of the vector from the center of mass of the TugRobot Satellite to the center of mass of the Target Satellite.

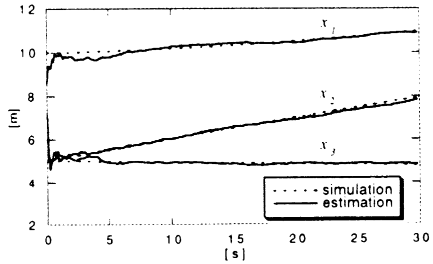
The results indicate that while the moments of inertia and the center of mass are well estimated, the other parameters are not. The reasons for this are that the distance between the center of mass and the thrusters is too small, and that the mass has little effect on the rotational motion. On the other hand, the successful estimation of some of the parameters is due to the fact that rotational motion is excited by thruster-firing so that the observability of the moment of inertia is increased.

The observability of these properties are well affected by the locations where the extra thrusters are attached. Both the input sequence and the attachment location of the thrusters should be taken into account to optimize the estimation.

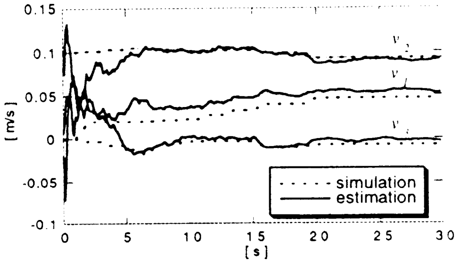
3.2 Result of Orbit Advance Simulation

As a numerical example, we consider an orbit advance maneuver along a circular orbit with a radius of 7.0×10^6[m], as shown in figure 5. In the following simulations, all mass properties are assumed to be known— that is, the results of the estimation obtained in the last section are not used to isolate the transportation problems from the effects of estimation errors of the mass properties.

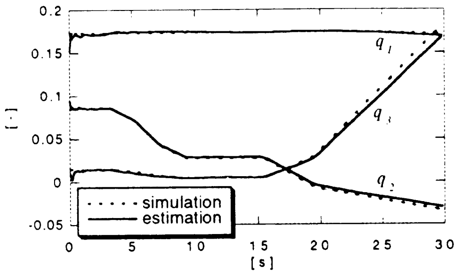
To simplify the analysis, the following assumptions are made: 1) the only external force acting is gravity; 2) gravitational moments are neglected; 3) assume impulsive thruster inputs; and 4) the change in mass due to fuel loss is



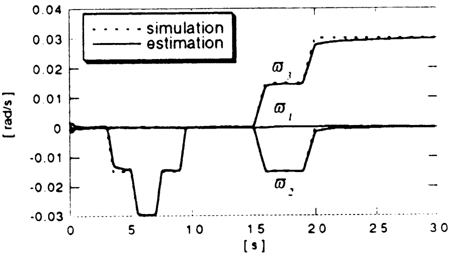
(a): Position



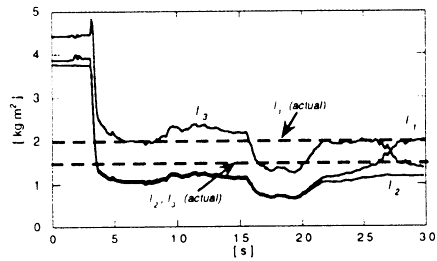
(b): Velocity



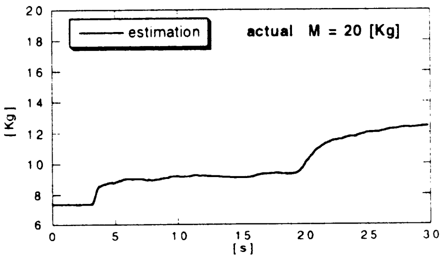
(c): Attitude(Quaternion)



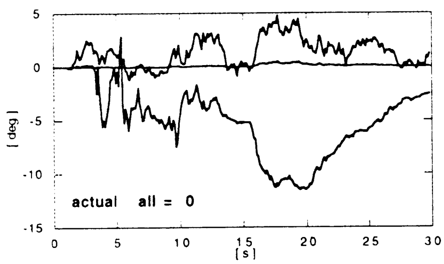
(d): Angular Velocity



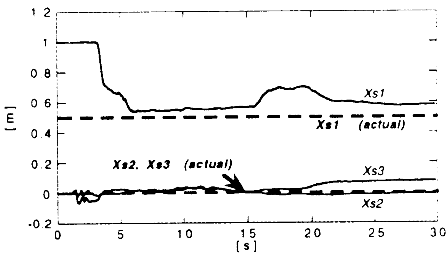
(e): Principal Moments of Inertia



(f): Mass



(g): Principal Axes



(h): Center of Mass

Figure 5: Estimation results.

Transactions on the Built Environment vol 19, © 1996 WIT Press, www.witpress.com, ISSN 1743-3509

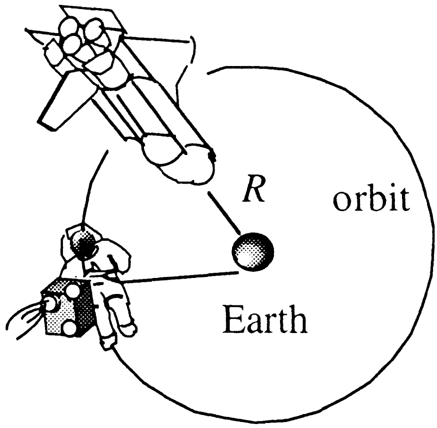
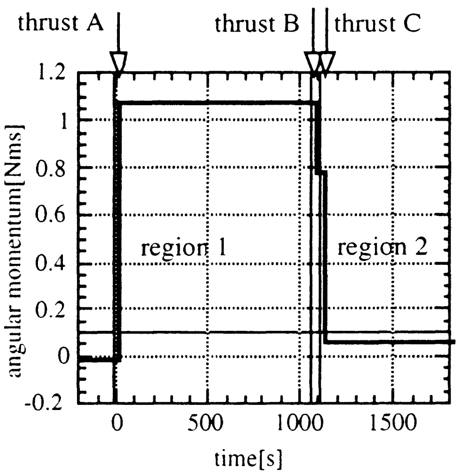


Figure 6: Simulation configuration.

neglected. In addition, the rendezvous conditions after the orbit advance are set as follows: 1) the angular momentum is less than 0.1[Kgm/s]; 2) the absolute error of the final location is less than 10[m]; and 3) the absolute error in orbital momentum is less than 0.01[Nms]. These requirements are appropriate for support operations because they are strict enough to cause little adverse effect on operations. As a result of searching through many sequences of thruster input under these conditions and for given initial conditions from the CW solution, we obtain several solutions.

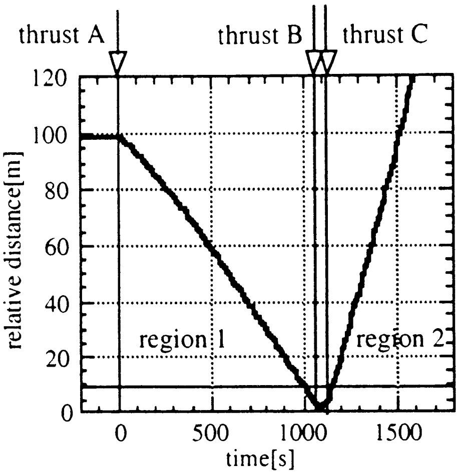
Figure 7 shows one of the solutions. In this case, three thruster impulses are considered. Thruster A is fired in order to meet the velocity requirements due to the CW solution, and the Combined Satellite advances in orbit to the target point



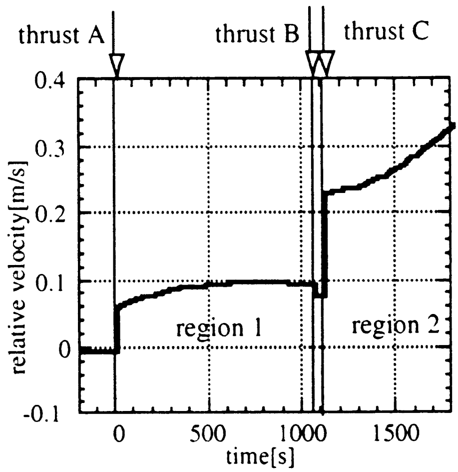
(a): Angular Momentum

Figure 7: Simulation results of orbit advance maneuver.

Transactions on the Built Environment vol 19, © 1996 WIT Press, www.witpress.com, ISSN 1743-3509



(b): Relative Distance



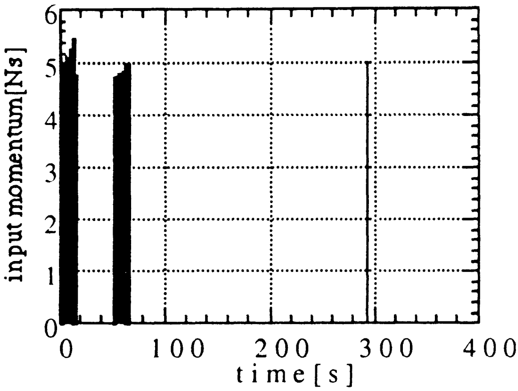
(c): Relative Velocity

Figure 7 : Simulation results of orbit advance maneuver.

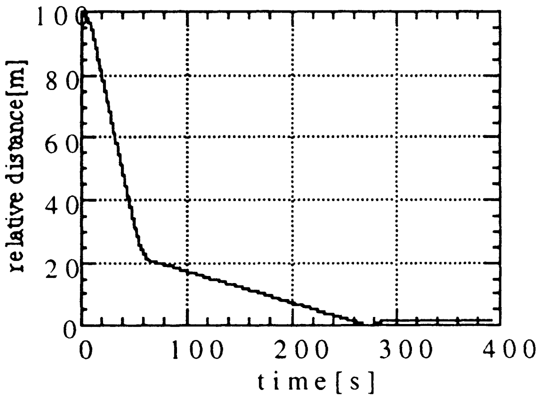
without thruster inputs in Region A. Thrusters B and C are fired in order to meet the rendezvous conditions. Region C shows the motion of the Combined Satellite after the rendezvous if no control is considered.

The results in Figure 8 correspond to different thruster inputs with 32 impulses in each case. According to these and many other simulations with different initial conditions and mass properties, we find that 1) there are solutions for almost every case with given initial conditions and mass properties and 2) that there are many cases in which the angular velocity can not be maintained small enough after the orbit advance is completed.

In this paper, because many possible thruster input sequences are considered by trial and error, there is not any theoretical strategy, per se, applied. Thus,



(a) Input momentum imparted by thruster



(b) Distance from target point

Figure 8 : Simulation results of orbit advance maneuver (different input case)

the obtained results do not mean that we can find appropriate inputs for every case. It is necessary to apply other nonlinear control or search methods to validate these results.

4 Conclusions

This paper demonstrates that it is possible for a TugRobot Satellite equipped with only thrusters to estimate the mass properties of an object and to control the object's translational and rotational motions properly for support of in-orbit operations, even in the case that the translational and rotational motions cannot be controlled independently. In future work, the mechanism by which the TugRobot Satellite clings to the Target Satellite will be studied, and the thruster input sequence needed for estimating the mass properties will be optimized. Theoretical approaches for orbit advance planning will also be studied.

Transactions on the Built Environment vol 19, © 1996 WIT Press, www.witpress.com, ISSN 1743-3509

References

1. Wiesel, W.E. *Spaceflight Dynamics*, McGraw-Hill, New York, 1992.

2. Kaplan, M.H. *Modern Spacecraft Dynamics & Control*, John Wiley & Sons, New York, 1976.

3. Lefferts, E.J., Markley, F.L. and Shuster, M.D. Kalman filtering for Spacecraft attitude Estimation, *Journal of Gudance, Control, and Dynamics*, 1982, **5**, 417-429.