DYNAMICS OF MORPHING ROBOTIC ARM WITH SPACE DEBRIS CAPTURE

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ABSTRACT

The space debris have been exponentially increasing which can damage active satellites by collision and therefore, their removal becomes necessary. The usage of a robotic arm to capture and remove active space debris seems to be promising for medium-scale debris and is the focus of this study. The existing robotic arms, attached with a chaser satellite, are designed as rigid structures with fixed geometry. Therefore, while capturing, the satellite has to come closer to debris which risks the life of the satellite itself and need significant attitude control. To avoid these issues, a "morphing robotic arm" is designed in this study. A robotic arm based on telescopic type morphing-beam is designed such that the length of the arm can be varied to make the capturing easy without the spacecraft going close to debris. In addition, the robotic arm is designed such that the vibration due to the impact of debris can be controlled. For dynamical analysis, initially, the robotic arm is approximated as a double pendulum with the variations in length executed by an active control system which results in a parametric type system. Elastic stiffness and mass distributions of robotic arm are modeled as equivalent bending spring and point mass of the double pendulum, respectively. Equations of motion derived with Euler-Lagrange formulation results in nonlinear, coupled, stiff-differential equations. A plastic-collision is considered for contact-dynamics between the space debris and robotic arm during the capturing process. The dynamic response of the morphing robotic arm due to debris capturing coupled with the variation of arm's length is studied. The active control system designed with linear model approximation shows the impact of debris capture can be minimized with least effort and the numerical results of nonlinear system are discussed.

Keywords: Robotic arm;Space debris removal;Morphing beam.

1. INTRODUCTION

Space debris is human-generated objects in space mainly in earth orbit which are not currently functional. Space debris is produced in many ways, such as nonfunctional spacecraft, abandoned launch vehicle, hypervelocity impacts with spacecraft wall, unburned particles from solid rocket motors or even paint flecks. Space debris is very fast-moving (usually 10 km/s), and its volume in orbit is also high, possessing a risk to current and future space missions. They are usually noncooperative and thus different from the usual targets of orbit servicing mission and possess the greatest challenge of how to capture and remove them without creating more reliably. J.C liou, through extensive simulation demonstrated that Kessler syndrome [9] is already engaged, meaning that debris would multiply in an unstoppable chain reaction without human intervention. To stabilize the environment, 5 to 10 space debris still needs to be removed as shown by a predictive model of NASA [12]. But currently, space debris is increasing fig [1]. Like large space debris, small space debris also has a high-risk factor [1] as given in Table1. Altitude close to 800 km is the most crowded orbit and altitude close to 600, 800 and 1000 km are the massiest orbits as most space debris with a mass over 50 kg are located [11].

According to French space agency (CNES),the actual debris is divided as given in Table 1.

Table 1. Debris Classification.

Size	No	Risk
Smaller than 1 cm	350,000,000	Low risk
Between 1cm and 10 cm	300,000	High risk
Bigger than 10 cm	16,000	Moderate risk

Many concepts have been proposed to capture and remove space debris, mainly divided into contact and contactless. Contact type consists of single and multiarm; tentacle mechanism embraces the target and makes a stiff connection between space debris and chase satellite [4]. Net capturing is also a contact type capturing mechanism in which net is thrown at space debris for establishing contact with them and then their removal [3]. Harpoon mechanism in which a tip is fixed from chaser satellite to be thrown for penetration in space debris object so by pulling they can be removed or moved to graveyard orbit [15]. Some contactless mechanism involves drag augmentation [2] and slingshot method [13].In this paper

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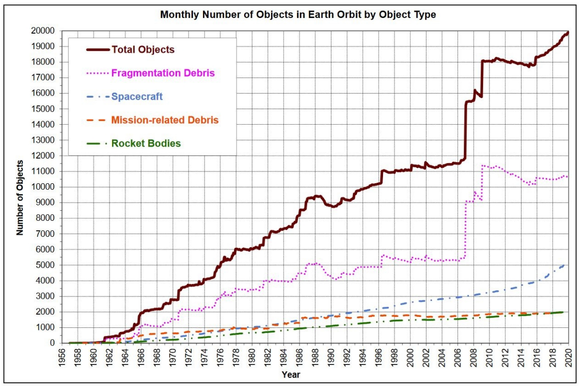

Figure 1. Monthly no of objects in earth's orbit [1]

design of a robotic arm is considered for space debris removal.

The robotic arm technology has been used in many on-orbit servicing missions such as canadarm2, orbital express DARPA, and many others [7]. But the target here is cooperative and non tumbling. The most important research areas for space debris capture with a robotic arm are minimizing the impact influence, detumbling, and attitude synchronization. When using a robotic arm, contact will happen, and thus impact effect is of great concern. Tumbling of space debris due to residual angular momentum also adds to difficulty [14]. JAXA has shown tumbling rate below 3 degree/s can be captured easily, and a tumbling rate between 3 degree/s and 30 degree/s can be detumbled by push contact. Attitude synchronization helps in directing robotic arms towards space debris during the critical capturing phase. Currently, many robotic technologies are in development for capturing a non-cooperative and tumbling target; DLR has been developing it for a mission named DEOS(Deutsche orbital servicing mission) [16], the FFERND arm is also designed, assembled, and tested [5], ATLAS [18] a two robotic arm controlled from the ground which can assemble space structure, robotic refueling task, and space debris removal.
This paper is organised as follows:-Section 2: Design of robotic arm, Section 3: Mathematical model of robotic arm , Section 4: Impact dynamics between robotic arm and space debris, Section 5: Controller is derived for the model, Section 6:Conclusion.

2. DESIGN OF MORPHING ROBOTIC ARM

The robotic spacecraft consists of a morphing [6] arm attached to the base satellite is shown in Fig. [2]. With the morphing capability of robotic arm, as shown in Fig. [3], the distance between chaser satellite and debris can be varied thus mimimizing the probability of debris colliding with the chaser satellite. Further, this retractable and extendable nature of the robotic arm requires a lesser

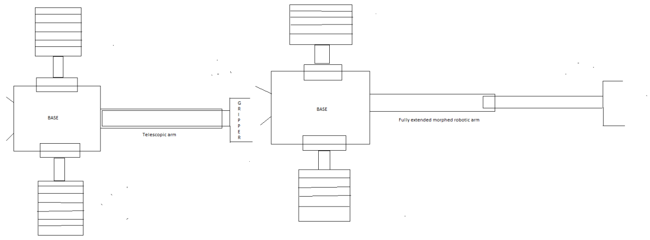

Figure 2. Design of Space craft with robotic arm

space in the launching vehicle compared to the traditional rigid, fixed geometry robotic arm.

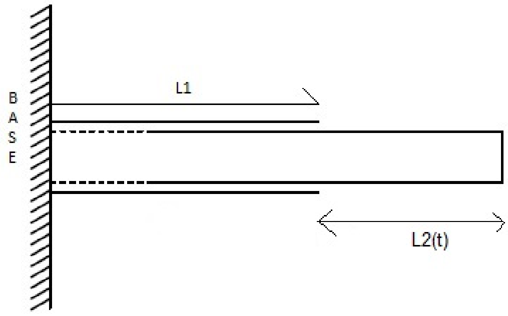

Figure 3. Morphing robotic arm section

3. DYNAMIC MODEL OF ROBOTIC ARM

In this section, dynamic model of the morphing arm based on telescopic type morphing beam is derived. The robotic arm is assumed to be fixed to the chaser satellite and the dynamics of base satellite base is not included in the model. The robotic arm is approximated as double mass pendulum with varying lengths and the springs attached to each link as shown in Fig [4]. The distributed mass of telescopic arm are approximated as two point masses M_1 and M_2 and the bending stiffness of each beam is represented by equivalent bending springs, K_1 and K_2. The length of the first arm, L_1 is considered as constant and the length of second arm $L_2(t)$ is is considered to vary with time as shown in Fig [4]. Now, Euler-lagrangian formulation is used to derive the mathematical model of system as given below:

Kinetic and potential energies of system

For M_1

$$T_1 = 0.5M_1(\dot{x_1}^2 + \dot{y_1}^2)$$

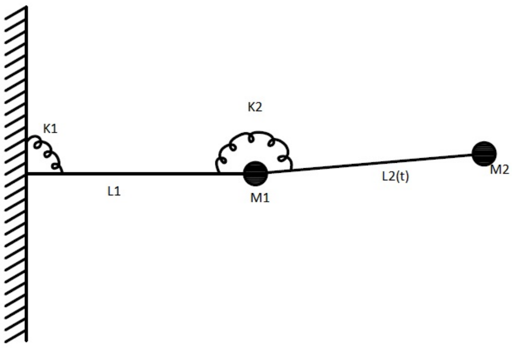

Figure 4. Lumped model of robotic arm

For M_2

$$T_2 = 0.5M_2(\dot{x_2}^2 + \dot{y_2}^2)$$

where the coordinates are given as

$$\begin{aligned} x_1 &= L_1 \sin(\theta) \\ y_1 &= L_1 \cos(\theta) \\ x_2 &= L_1 \sin(\theta) + L_2 \sin(\alpha) \\ y_2 &= L_1 \cos(\theta) + L_2 \cos(\alpha) \end{aligned}$$

Now, differentiating the coordinates with respect to time

$$\begin{aligned} \dot{x_1} &= L_1 \cos(\theta)\dot{\theta} \\ \dot{y_1} &= -L_1 \sin(\theta)\dot{\theta} \end{aligned}$$

$$\begin{aligned} \dot{x_2} &= L_1 \cos(\theta)\dot{\theta} + L_2 \cos(\alpha)(\dot{\alpha}) + \dot{L_2} \sin(\alpha) \\ \dot{y_2} &= -L_1 \sin(\theta)\dot{\theta} - L_2 \sin(\alpha)(\dot{\alpha}) + \dot{L_2} \cos(\alpha) \end{aligned}$$

Strain energy in springs

$$V = 0.5K_1(\theta)^2 + 0.5K_2(\theta - \alpha)^2$$

Now, the forces f_1 and f_2 are the actuator forces applied at joint location for robotic arm control.

Substituting the above expressions in Euler Lagrangian formula, the equation of motion is derived as non-linear, coupled differential equations given below:

$$\begin{aligned} (M_1{+}M_2)L_1^2\ddot{\theta}{+}M_2L_1L_2\cos(\theta{-}\alpha)\ddot{\alpha}{-}M_2L_1\sin(\theta{-}\alpha)\ddot{L_2}+ \\ 2M_2L_1\dot{L_2}\dot{\alpha}\cos(\theta - \alpha) + M_2L_1L_2\sin(\theta - \alpha)(\dot{\alpha})^2+ \\ k_1(\theta) + k_2(\theta - \alpha) \\ = f_1 \end{aligned} \quad (1)$$

$$\begin{aligned} M_2L_2^2\ddot{\alpha}{+}M_2L_1L_2\cos(\theta{-}\alpha)\ddot{\theta}{-}M_2L_1L_2\sin(\theta{-}\alpha)(\dot{\theta})^2+ \\ 2M_2L_2\dot{L_2}\dot{\alpha} - k_2(\theta - \alpha) \\ = f_2 \end{aligned} \quad (2)$$

4. DEBRIS IMPACT MODELING

The impact of the space debris on the robotic arm is modeled in this section. The dynamics of capturing the space debris is mainly analyzed through impact or contact analysis. The impact is a complex phenomenon in which two bodies collide with each other. If the impact is of brief duration, rapid dissipation of energy occurs and the dynamic response of robotic arm decays in short duration. However, if the contact occurs over a finite time, the dynamics will have secondary phases such as slipping, sticking, and reverse motion during the capturing phase [8]. In this study, the collinear impact of bodies with e(coefficient of restitution)=0 for perfectly inelastic collision is considered . Therefore, the energy conservation principle is applied to convert the impact of debris as the initial conditions applied to the Mass, M_2 of the above system. Also, due to inelastic collision assumption, the bodies are considered to stick together after impact.

5. CONTROL SYSTEM FOR DEBRIS IMPACT

In this section, a control system is designed to mimimize the dynamic response of the robotic arm induced by debris impact. The linearized model is used to develop the LQR model and the control system is then verified for the nonlinear model. The non-linear equations of motion are linearized near stationary points for analysis [17]. The system parameter values used for the analysis are given in Table 2.

Now, using the Jacobian linearization, the stationary values are found to be
$\theta = 0; \dot{\theta} = 0$; $\alpha = 0; \dot{\alpha} = 0; f_1 = 0$; $f_2 = 0$;

[Table 2] System parameter values:

Parameter	Value
M1 (kg)	1
M2 (kg)	0.5
L1 (m)	1
L0 (m)	1
k	0.5
K2 (N-m)	5000
K1 (N-m)	5000

An optimal regulator is considered for the linearized system $\dot{x} = Ax + Bu$. Here, the matrix 'K', for the control law $u(t) = -Kx(t)$, is found out such that it minimize the performance index
J =$\int_0^\infty (x^T Qx + u^T Ru)dt.$
Here, the 'Q' and 'R' determines the relative importance of the error and the expenditure of energy [10].

The optimal matrix 'K' is given by $K = R^{-1}B^T P$ where P is found by reduced riccati equation :
$A^T P + PA - PBR^{-1}B^T P + Q = 0$

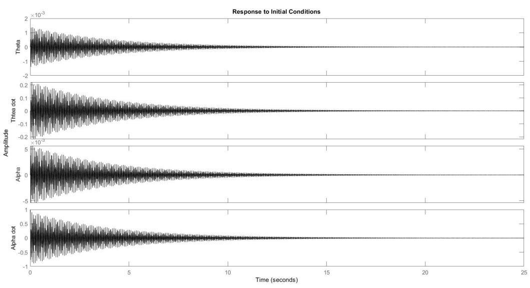

Figure 5. Dynamics of linear system with initial value $\dot{\alpha}$ = 0.1

Now, the values of weight matrix are choosen for LQR controller based on the criteria that the optimal values of energy required for actuator and optimal time required for reaching steady state. The values for the robotic arm system are found as
Q=[500,0,0,0;0,500,0,0;0,0,500,0;0,0,0,500];
R=[5000,0;0;5000]

Three cases of dynamics and control of robotic arm are studied.
Case 1: Initially, the dynamics of system with linear model with the derived control system is investigated. The dynamic response, for an initial disturbance due to debris, is shown in Fig 5. The system response decays within a short period. Also, the Eigen values of controlled system $(A - B * K)$ are found to lie on the left half of stability diagram making the system stable.

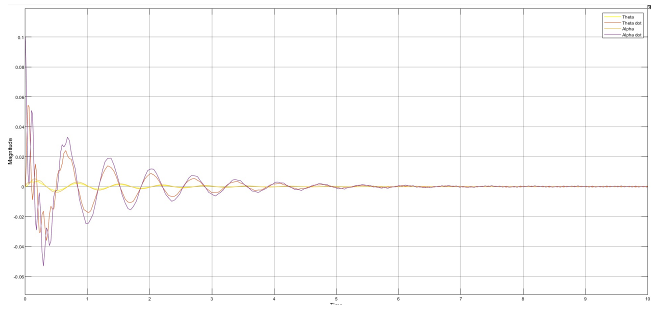

Figure 6. Controller applied to non-linear model with $\dot{L_2}$ = 0

Case 2: In the second case, the same controller derived for linear system is applied to non-linear system, where it considered that $\dot{L_2} = 0$. That is, this case represent the nonlinear robotic arm, without the morphing process. The response is shown in Fig [6]. As shown in Fig. [6], the states of output are going to stable position with help of designed LQR controller.

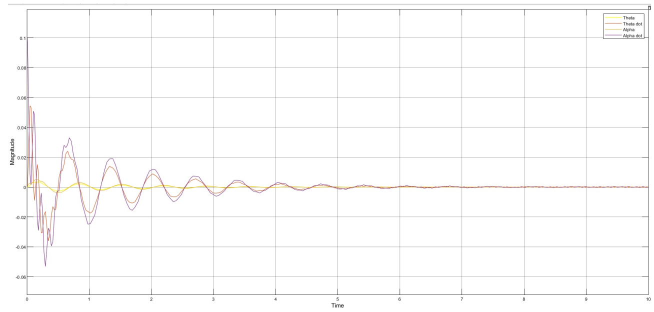

Figure 7. Controller applied to non-linear model with L_2 = lo+$ksin(\theta)$

Case 3: In the third case, the control of robotic arm with morphing dynamics is considered. The variation in the arm $L2$ is taken as a function of θ, which implicitly depends on time. Controller derived with linearized system of case 1, is applied. The system dynamics is shown in Fig [7] which shows that the response becomes stable with the help of controller in short period. In all three cases, the system response due to debris impact are minimized within a short duration.

The above preliminary analysis and control show the effectiveness and feasibility of the morphing robotic arm for space debris capture.

6. CONCLUSION

A morphing robotic arm is designed to capture the space debris with a flexibility of varying the length between the chaser satellite and debris. The robotic arm is approximately modeled as a double pendulum with varying length consisting of lumped mass and equivalent bending stiffness of the telescopic beam. The mathematical model of the system ends up as a coupled, nonlinear differential equations with varying coefficients. The impact of debris is modeld as inelastic collision and the dynamic response due to debris impact is studied. An active control system is designed to minimize the response due to impact. The LQR (Linear quadratic regulator) optimum controller is derived with the linearized model of the system. The controller derived is then applied to the non-linear equation of motions with morphing robotic arm. The debris induced dynamic response is found to be minimized in short duration. The initial morphing robotic arm design proposed in this study is found to be an effective way to capture the debris. However, the improvements in modeling such as continuous beam modeling of robotic arm, dynamic contact analysis rather than impact force analysis and coupled dynamics of robotic arm with satellite base have to be included and are being studied.

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