# Effects of Space Debris Collision on A Satellite with 5-Bar Linkage Robot Operation

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† Presented at the 2nd Innovation Aviation & Aerospace Industry - International Conference 2021, 28-30 June 2021; Available online: https://iaai-2021.sciforum.net, https://iaai.asia/

Published: 1 July 2021

**Abstract:** One of the most common damages of satellites is occurred by collisions of space debris. The collision of the debris is unavoidable during the space operation; therefore, a study of physical effects in relation to the collision must be conducted in order to understand the consequences. This article proposes an experiment setup of a satellite with a 5-bar linkage planar robot working inside. The structure, kinematics, and control architecture of the robot are presented. In addition, the relationship between satellite damage and the debris' size and speed, which vary according to the altitude, is analyzed. Consequently, the designs of small satellites' orbits can be improved by using this study. As a result, the final condition of an operational satellite structure against a collision of valuable space debris can be predicted. This study leads to future work where the design rules for reducing the effect of payload variability will be developed.

**Keywords:** Satellite; 5-bar linkage robot; debris collision

## 1. Introduction

A CubeSat is a small satellite with the size of 10 cm × 10 cm × 10 cm (1U). Since the 2000s, they have been on focused among educational and engineering projects, which extensively aim for designing the mission, building, and testing with an actual satellite. Until 2015s, around 465 CubeSats were launched to the Earth orbit [1]. Currently, the number of space activities rises dramatically; therefore, the number of space debris has increased accordingly. In 2019, it is estimated that more than 19,000 space debris exist in space due to launching, fragmentation, explosions, and collision [2].

On the other hand, CubeSats regularly encounter problems in regard to space debris; as a result, 50-75% of them fail to operate [3]. Nowadays, the researchers emphasize on reduction of the collision probability and technical design of the satellite to avoid space debris. Active control techniques are implemented in around 80% of CubeSats [4]. However, avoidance of space debris is still challenging due to two main factors: the speed of debris and the moments of CubeSats.

This paper is organized as follows. As a payload, the design of a robot system that will be used for conducting experiment tasks inside the 3U CubeSat. *Section 2* presents the structure design and kinematics. *Section 3* presents the system architecture and control of the robot. In *Section 4*, the effects of the collisions between the satellite and space debris are studied. The conclusion and future work are discussed in *Section 5.*

**2. System overview and robot kinematics**

A 2-DOF 5-bar linkage parallel robot is equipped inside the 3U satellite. The main components (see Figure 1) consist of (a) robot (b) controller (c) camera and (d) ADCS. The robot and camera are controlled and monitored by the program run in the controller, and the ADCS helps to stabilize the satellite when the robot moves. The system is designed to operate in two dimensions within 90 mm x 90 mm workspace. In this case, the motion control of the robot in a space environment with collision incidents will be studied. The aspherical locating pin is attached to the robot's end-effector; therefore, the movement path can be tracked by a camera.

In comparison to the serial mechanism, this parallel 5-bar linkage mechanism is selected due to its high rigidity and accuracy. The robot's links are designed to be low inertia by placing motors at the base, which is an advantage for precision motion control (see Figure 2). The two brushless DC motors are mounted at the ends of link-1 and link-2. The position of the end-effector ($\boldsymbol{P}_r$) can be controlled with $\boldsymbol{\theta}_1$ and $\boldsymbol{\theta}_2$ with the following inverse kinematics equation [5].

$$[\theta_1, \theta_2] = \left[2\arctan\left(\frac{-F_1 \pm \sqrt{E_1^2 + F_1^2 - G_1^2}}{G_1 - E_1}\right), 2\arctan\left(\frac{-F_2 \pm \sqrt{E_2^2 + F_2^2 - G_2^2}}{G_2 - E_2}\right)\right]$$

Where

$E_1 = -2l_aP_x$ $\quad F_1 = -2l_aP_y$ $\quad G_1 = l_a^2 - l_b^2 + P_x^2 + P_y^2$

$E_2 = 2l_a(-P_x + l_c)$ $\quad F_2 = -2l_aP_y$ $\quad G_2 = l_c^2 + l_a^2 - l_b^2 + P_x^2 + P_y^2 - 2l_cP_x$

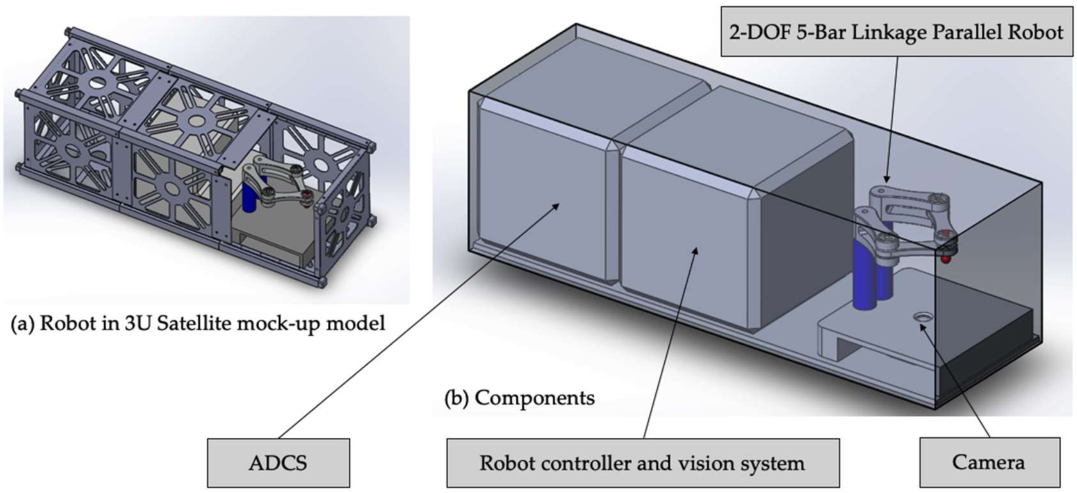
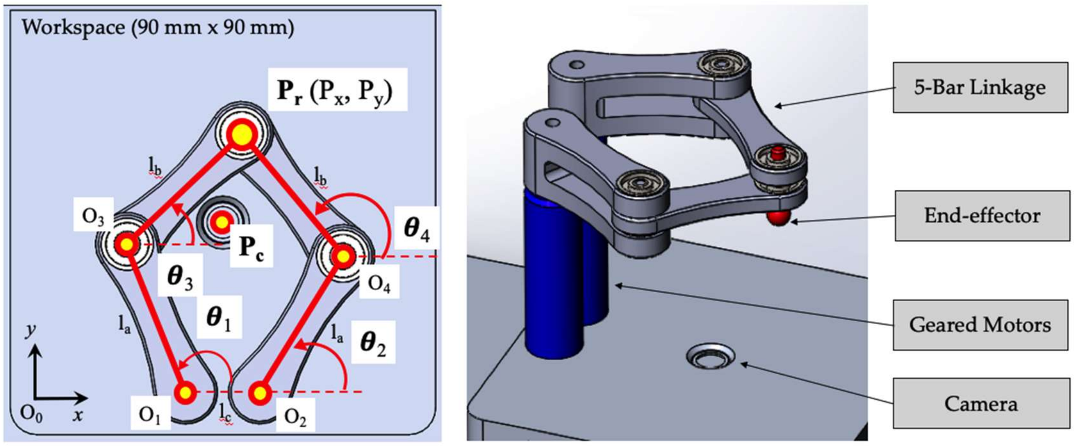



**Figure 1.** Components in 3U satellite




(a) Schematic diagram (b) 3D model of 5-bar linkage robot

**Figure 2.** Schematic diagram and model of 5-bar linkage robot

## 3. System architecture and control

The system consists of 2 main blocks: (a) *robot arm area block* and (b) *main controller block* (see Figure 3). For the robot arm area block, there are both mechanics and mechatronics parts. The *brushless DC motors* are selected from many versatile advantages for robotics applications such as high torque to weight ratio, low noise, and longer lifetime in comparison to brushed DC motors. The *stabilizer actuator* is included in the system to compensate for an unbalanced momentum from the motion of the robot arm by calculating the *momentum compensator* block inside the *microcontroller*. The *programmer* circuit is also included in the controller board so that the system can be edited the program after launch. The *camera* is added to monitor the robot arm motion using the object detection block to reduce the data to be sent to the station.

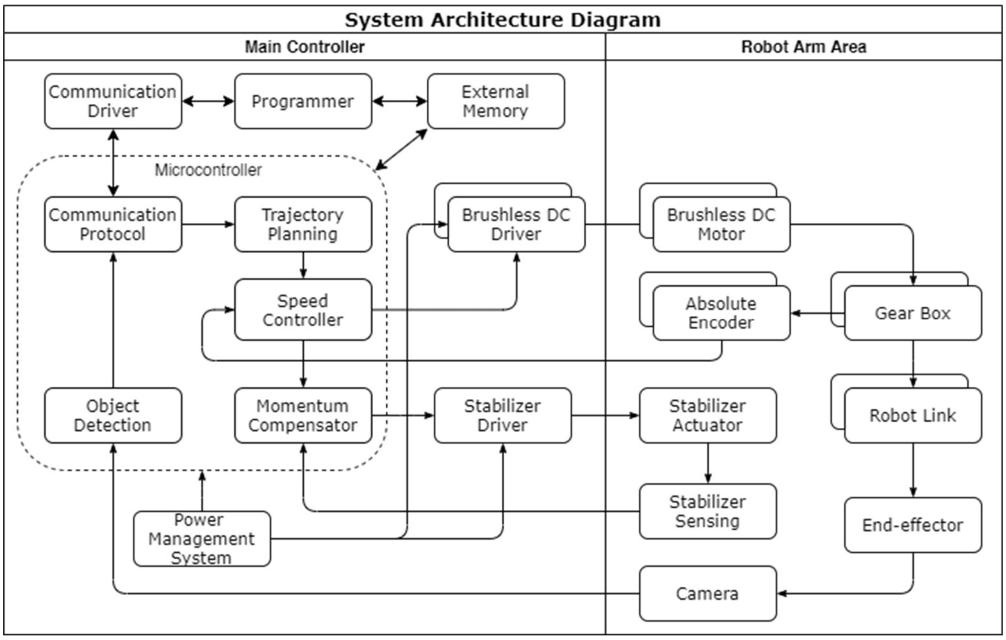



**Figure 3.** System Architecture Diagram.

## 4. Predicted effects from the collision

In this section, we study how collisions between the satellite and space debris can affect the flight parameters (i.e., changes in altitude and direction) or lead to an end-of-mission of the operating satellite in the Low Earth Orbit (LEO). The sizes of debris in LEO can range $10^{-6}$ – 10 m in diameter. The effects of the collisions between a satellite and debris with intermediate size (with a mass around 0.01 – 1 percent of the satellite's mass) are studied to estimate the state of the satellite after a collision.

All debris are assumed to orbit the Earth in circular motions at the same altitude as the satellite does (200 km), but their orbital planes are random (see Figure 4a). As a result, the relative velocity between the debris and the satellite depends on the incident angle during the impact. From the assumptions, the impact speed ($v_{rel}$) varies between 0 and 2v (where v is the orbital speed). A collision is considered catastrophic if the condition $(1/2)(m_{debris}/m_{sat})v_{rel}^2 \geq 40$ J/gram is met [6]. After a catastrophic collision, the satellite will be considered out of commission.

The vertical line in the plot (see Figure 4b) suggests the critical angle ($\boldsymbol{\theta}_C$)such that the relative speed is large enough to cause a catastrophic event. As it turns out, collisions under the chosen mass at this altitude are more likely to put the satellite out of commission rather than knock it off to a lower orbit and crash on the Earth.

If we assume that collisions from all directions are equally likely, the possibility that a collision with the given *mass ratio* $(m_{debris}/m_{sat})$ will be catastrophic is (180 - $\boldsymbol{\theta}_C$)/180. The plot between the mass ratio and the probability of having a catastrophic collision is shown in Figure 4b.

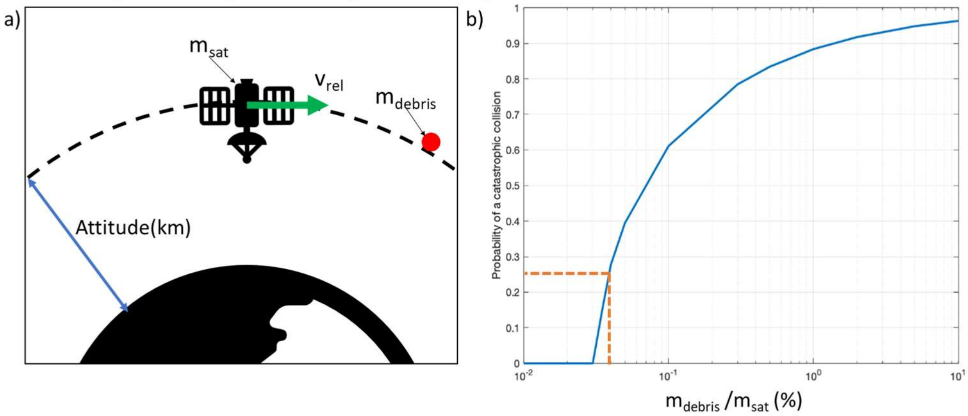



**Figure 4.** (a) The configuration of collision and (b) is the result of the probability of a catastrophic collision and mass ratio [note that: the orange dash line is the risk of a catastrophic event]

## 5. Conclusion and Future work

The result here can be used for assessing the risk of a catastrophic event at the chosen altitude. For example, if the acceptable value of a catastrophic event is set at 25%. The maximum of debris is 1.2g at a 3 kg satellite because it translates to a mass ratio of 0.04%. This mass corresponds to debris with a diameter around 0.5 - 1 cm, assuming the mass density of debris can be between 1 to 10 g/cm$^3$. With the information about debris size at such altitude, catastrophic events during operation time can be estimated. Alternatively, another altitude may be chosen to minimize catastrophic collisions.

Future work for orbit simulation: The next step for the collision simulation will be determining the mean free path of the satellite. This can be done by incorporating information about debris population in LEO with the current result of a probability of a catastrophic collision to estimate how far a satellite before can travel before it runs into end-of-mission collision.

Another work is to study the dynamics of the satellite after a small collision. To make sure that the on-board actuators are capable of readjusting the satellite's orientation (altitude, spin) with an acceptable response time. Theory in regard to advanced dynamic control will be involved.

**Acknowledgments:** This work was partially supported by (a) the NUAA Research Fund (P.N.) and (b) NXPO as part of project “Promotion of Robotics for All & Development of Robotics Innovators, Researchers, Engineers, and Startups”

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