SYSTEM REQUIREMENTS ELICITATION AND CONCEPTUALIZATION FOR A NOVEL SPACE ROBOT SUSPENSION SYSTEM

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ABSTRACT

Robotic manipulators play a pivotal role in space exploration and pave the way for satellite lifetime extensions, orbital asset inspections, and deorbiting. However, space robots are tested under Earth's gravity despite being designed for zero gravity. Most space robots are constructed such that they cannot bear the Earth's gravitational loads, necessitating an external support system for on-ground tests. Conventional test facilities, however, face significant limitations including workspace constraints and influence of the dynamics. Against this background, a novel suspension system for non-gravity-bearing space robots is planned. To address this challenge, the paper reviews mechanical suspension systems for space robot test setups and outlines essential requirements for the novel suspension system. A comparative analysis of concepts that fulfill the stated requirements complements the literature. The findings highlight the cable-driven parallel robot as an optimal trade-off solution.

Key words: space; robotics; gravity compensation; offload mechanism; suspension system.

1. INTRODUCTION

Space robotics plays a crucial role in the domain of space exploration and creates numerous opportunities for future space missions [1]. Free-flying robots mounted on satellites or space stations pave the way for manifold possibilities in future space missions including satellite lifetime extensions, orbital asset inspections, and deorbiting [2]. The Canadarm2 [1] provides an example of a successful robot that has assisted with docking maneuvers, assembly, and maintenance on the International Space Station since 2001. Given their relevance, testing space robots, their diverse components, and their functions is crucial. Once they have been deployed, changing or repairing them becomes a difficult task. Thus, realistic on-ground tests of the robotic system are important to make sure that the robot performs reliably [3]. However, on-ground tests of space robots pose a significant challenge: Space robots are designed to operate in zero gravity, but are tested under the influence of Earth's gravity. Above this, serial space robots are limited in the torque necessary to move on-ground, i.e., they cannot withstand their weight in Earth's gravity [1].

Motivated by the challenge of testing space robots on ground, this manuscript covers the groundwork of designing a novel space robot suspension system. This prompts the following guiding research question: *Which requirements are significant in the context of designing a suspension system for a space robot, and subsequently, which concept aligns most effectively with fulfilling these requirements?* To address this research question, we combine literature review and requirement elicitation to analyze the feasibility of different mechanical solutions.

The paper is structured as follows: First, the literature review provides an overview of existing mechanical solutions for space robot tests. Secondly, the requirement elicitation states the essential requirements for designing a novel suspension system for space robots. As a result, the concept solutions are qualitatively compared based on the stated requirements. The discussion section evaluates the results and contextualizes them on a broader scale.

2. LITERATURE REVIEW AND DESIGN CONCEPTS

Most test facilities [4] for non-gravity-bearing space robots are based on planar air bearings [5]. Other concepts are helium balloons [6], neutral buoyancy [7], free-fall/parabolic flights [8], rail-based suspension systems [9], and cable-driven suspension systems. The subsequent sections provide insights into these design concepts.

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[1] `www.asc-csa.gc.ca/eng/iss/canadarm2`

2.1. Air Bearing

Air bearings are the most commonly used concept in space mechanism test facilities. The space asset to be tested is mounted on one or several platforms that are placed on a flat floor. The platform holds an air tank which creates a thin layer of air between the flat floor and the platform. This allows the space asset to move nearly frictionless in a horizontal plane. This method is limited to the accuracy of the flatness of the floor, small inaccuracies lead to pulling forces to the valleys of the flat floor. The *Orbital Robotics Lab* at *ESA ESTEC* (see Fig. 1) forms an example of an air bearing test setup [5], [10], [11].

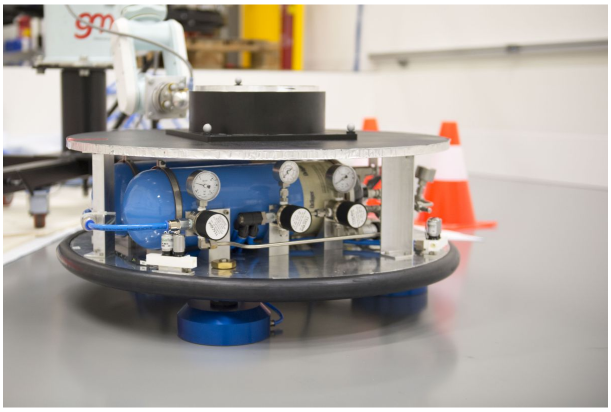

Figure 1. Air bearing setup for testing space assets in two-dimensional workspace (Credit: ESA–G. Porter, CC BY-SA 3.0 IGO)

2.2. Helium Balloons

Helium balloons use the uplift force of helium in the air to support space structures. They are commonly used for supporting large structural elements such as solar sails and solar arrays when deploying them during on-ground tests. The helium balloon is connected to one or several locations at the structure and provides a vertical force that prevents large solar structures from collapsing. Helium balloons are usually large and feature a high inertia. [6]

2.3. Neutral buoyancy

Neutral buoyancy uses the uplift force of objects in water to compensate for gravitational force. Although this method does not intrinsically cancel out gravity, it becomes very close to zero gravity. This is often used for astronaut training as shown in Fig. 2. However, neutral buoyancy is strongly affected by hydrodynamics effects which leads to damping. The *Space Systems Laboratory*[2] of the *University of Maryland* operates a $15\,\mathrm{m}$ diameter and $7\,\mathrm{m}$ deep water tank which is used to test space robots in microgravity. For these tests, the space robot needs to be modified to be waterproof. [4], [7]

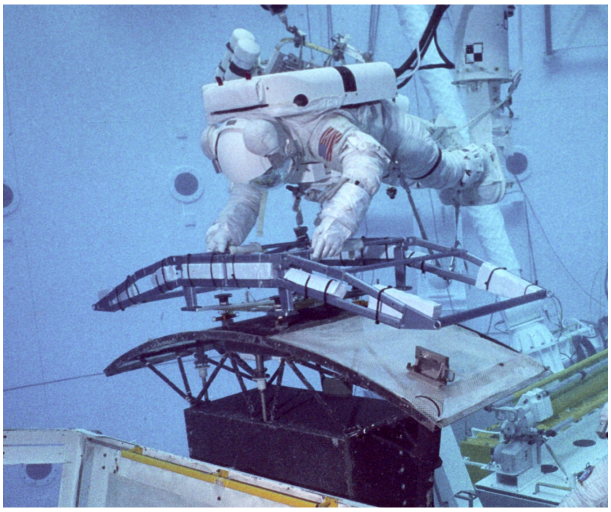

Figure 2. Underwater facilities provide a zero-gravity environment and are frequently used for astronaut training (Credits: NASA)

2.4. Free-fall/Parabolic Flights

Free-fall/parabolic flights (see Fig. 3) provide nearly zero gravity, but only for a few seconds. Parabolic flights are performed using a refitted aircraft that flies a parabolic path which results in about $20\,\mathrm{s}$ of zero gravity. Sawada *et al.* tested a space robot during a parabolic flight and obtained current measurements which are compared with results from on-ground experiments. They found out that basic movements in position control do not lead to different behavior of the arm. However, friction plays a critical role as it decreases by $15\,\%$ when compared to the robot operation on ground [8]. Drop towers form an alternative to parabolic flights, e.g. the *Einstein Elevator* (see Fig. 4) at the University of Hannover, Germany, which provides $4\,\mathrm{s}$ of less than 10^{-6} g. Free-fall tests are easier to perform but offer less space and time for the experiment. However, the accelerating profiles during the experiment can damage the space robot. [12], [13]

2.5. Rail-based Mechanical Suspension Systems

Rail-based suspension systems often use a Gantry crane for the horizontal movement to follow the space robot's trajectory. The vertical force can be applied passively using counterweights [14], [15] or actively using winches as shown in Fig. 5 [9]. Mechanical suspension systems are often more flexible in positioning. Schultheiß [16] describes several concepts to support a solar array during a pure horizontal movement. Other systems also include a vertical degree of freedom. They are connected at one or more points to the space robot. [14], [15]

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[2] `www.aero.umd.edu/research/space-systems-lab`

Figure 3. Parabolic flights (Photo: DLR, CC BY-NC-ND 3.0)

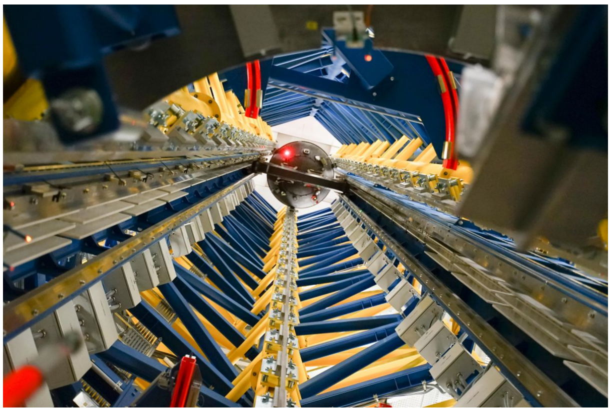

Figure 4. Fee-fall tower Einstein-Elevator *at the Hannover Institute of Technology (Credits: Leibniz Universität Hannover/Marie-Luise Kolb)*

Figure 5. A astronaut uses the rail-based Active Response Gravity Offload System (ARGOS) which allows to simulate a zero-gravity environment. (Credits: NASA)

2.6. Cable-Driven Parallel Mechanical Suspension Systems

Cable-driven parallel robots find applications in several fields such as automated construction [17]–[19], logistics [20], [21], or rehab purposes [22]. These robots consist of cables that are linked to a mobile platform possessing multiple degrees of freedom and are coiled around motorized cable drums. The cables are directed through pulleys to maneuver within the workspace. Cable-driven parallel robots feature attributes such as lightweight construction, expansive workspace, and exceptional dynamics [23]. This makes them well-suited for suspension systems as shown in Fig. 6. Algorithms such as by De Stefano *et al.* [24] allow to compensate for gravity using an external carrier (e.g. a cable robot) and internal robot joint torques.

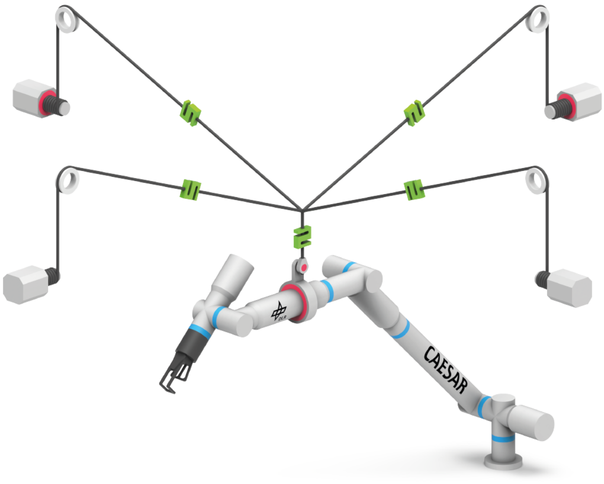

Figure 6. A cable-driven parallel robot can be used for suspending a space robot arm. (Credits: German Aerospace Center DLR)

3. REQUIREMENT ELICITATION

In this section, we outline the requirements for a novel suspension system that is essential to facilitating the development and qualification of a space robot. The requirements are grouped into *gravity compensation*, *geometric flexibility*, *dynamics analysis capability*, and *usability*. The requirements can be used to evaluate and compare design concepts for a space robot suspension system.

3.1. Gravity Compensation

The main purpose of a suspension system is to mechanically support a space robot and to compensate for gravitational effects. This comes with the following requirements:

Reducing Joint Torques: Most space robots are designed for operating in zero gravity. However, the tests are performed under gravity. Thus, movements lead to easily reaching the joint torque limits. A suspension system should reduce the joint loads.

Zero Gravity: A suspension system is never ideal and thus cannot cancel out all effects of gravity. However, some systems are more suitable to create an environment closer to zero gravity than others.

Adaptable Gravity Environment: Other environments apart from zero-gravity need to be created by the suspension system, such as the Moon's or Mars' gravity environment.

3.2. Geometric Flexibility

To develop the space robotic arm and validate its performance, it is crucial to gather measurements in all kinematic configurations of the space robot. Many high-level applications, such as grasping strategies for catching satellites, vision algorithms for navigation or complex recovery movements need to be tested and validated. They require the space robot to move in all six degree of freedom (DoF) [25]. Thus, the suspension system needs to cover the complete or at least a large part of the workspace of the space robot.

Extended Workspace: A robot arm usually is characterized by a spherical workspace with the radius of the space robot's length. This workspace needs to be covered by the suspension system.

6-DoF Work Envelope: Many robotic tasks such as grasping, vision-based approaches, or rapid retraction trajectories require the usage of the full, 6-DoF workspace envelope.

3.3. Dynamics Analysis Capability

The suspension system is used to perform an analysis of the space robot's dynamics and to test the controller of the space robot. However, the space robot and the suspension system form a coupled system with coupled dynamics. Analyzing the space robot dynamics always includes analyzing both systems. Thus, the characteristics of the suspension system needs to be clear. It is essential to distinctly delineate the behavior caused by the space robot itself and that which stems from the suspension system.

High Vibration Bandwidth: A high vibration bandwidth allows the suspension system to not influence the space robot during dynamic movements thereby enabling a dynamics analysis. This plays a role when testing the accuracy and its behavior when in contact with other elements or during high-velocity movements such as collision avoidance maneuvers.

Suspension Force Observation: To allow computing the force equilibrium of the space robot, the applied force from the suspension system needs to be measurable.

Non-Invasive Testing: This describes if the space robot needs to be modified to run a test. No changes should be necessary to stay as close as possible to the flight model of the arm. For example, performing tests underwater requires that the system is waterproof. This will change the properties of the tested system which reduces the applicable outcome of the test.

3.4. Usability

It is planned to use the suspension system for validation and development. Thus, the handling of the system is a crucial factor. It needs to be easy to operate with the suspension system to avoid long development periods.

Unlimited Experiment Duration: We demand that the testing duration is not limited in time. This allows extensive development and testing.

Compactness and Affordability: The complexity of the setup should be low. This includes size, cost, mass, and the effort of setting up the suspension system.

Low Experiment Effort: The effort using the suspension system needs to be low to reduce the workload during the development and validation phase of the space robot.

4. RESULTS – CONCEPT EVALUATION

This section compares design concepts for space robot suspension systems as they are listed in Section 2 by the requirements from Section 3. The qualitative rating is described with the symbols - -, -, o, +, ++ in increasing order of suitability. Table 1 shows the result and the following provides details about the rating.

Air bearings are limited to only zero gravity environment and the size of the workspace is limited to the size of the air bed. This concept creates zero-gravity by limiting the workspace to a horizontal plane which results in only 3-DoF movements (two planar, one rotation direction) [4]. Due to the additional mass, the vibration bandwidth of the systems is strongly lowered and the applied support forces can be measured using force torque sensors [26]. Apart from the mounting to the air bearing platform, there are no changes necessary to the space robot. The experiment time duration is limited by the size of the air bottles.

Helium balloons are mounted only on one or multiple points on the robotic structure. The uplift force is fixed during motion, but with some effort, it is possible to adjust it with additional weights [6]. Helium balloons can cover a large workspace but they add a minimum 16% of the inertia which strongly alters the dynamics [27]. Additionally, due to drag, they have strong viscous damping

Table 1. Comparative analysis of suspension systems concepts based on performance criteria

Suspension Concept **Requirement**	**Air Bearing**	**Helium Balloons**	**Neutral Buoyancy**	**Free-falling**	**Rail-based**	**Cable-driven**
Gravity Compensation						
Reducing Joint Torques	++	++	++	++	++	++
Zero Gravity	+	o	+	+	+	+
Adaptable Gravity Environment	- -	o	o	- -	++	++
Geometric Flexibility						
Extended Workspace	+	++	++	- -	+	+
6-DoF Work Envelope	- -	++	++	++	++	++
Dynamics Analysis Capability						
High Vibration Bandwidth	-	- -	- -	++[3]	-	++
Observation Capability	++	++	- -	++[3]	++	++
Non-Invasive Testing	+	+	- -	++	+	+
Usability						
Unlimited Experiment Duration	o	++	+	- -	++	++
Compactness and Affordability	o	++	- -	- -	o	+
Low Experiment Effort	+	+	- -	- -	+	+

and vertical stiffness. Helium balloons need a large facility due to its necessary dimensions which increases the space requirement for the testing facility.

Underwater experiments utilize neutral buoyancy to compensate for the gravity effect by leveraging the buoyant properties of material in water, resulting in a practical, but not perfect simulation of zero-gravity conditions. Using different materials or additional masses, the force can be adapted to different gravity environments. The work envelope of the space robot is practically not limited. However, the water's density slows down and strongly dampens the robot's movements. As a strong disadvantage, the space robot needs to be waterproof and thus strongly adapted to make it suitable for neutral buoyancy tests. [7]

Free-falling towers and parabolic flights provide zero gravity which means that the gravitational forces do not need to be compensated. However, the flight dynamics of the aircraft leads to non-smooth motions deteriorating the zero-gravity environment. The deceleration phase leads to high loads on the system. Free-falling towers and parabolic flights are strongly limited in space, but do not alter the dynamics of the robot. The drawback is evident when focusing on the handling aspect: This concept only provides zero gravity for several seconds with comparatively high effort. [12], [28]

Rail-based mechanical suspension systems allow to provide an adaptable suspension force in a comparatively large workspace. It is possible to use more than one connection point to the space robot and thus increase the zero-gravity approximation. However, the heavy structure leads to a low mechanical modes [29] and strong friction effects. By using force sensors, the applied force can be observed.

Cable-driven suspension systems rely on cables mounted on actuated winches. A control software coordinates the movements. The suspension force can be adapted to different configurations and simulated gravity environments. Cable-based cable robots can cover a large workspace, as used for instance in the five-hundred-meter *Aperture Spherical Radio Telescope* [30]. Full 6-DoF movements are possible using a suitable coupling mechanism between the suspension system and the space robot. Due to the lightweight design, the dynamics of the system is high [23]. By using force sensors, the applied force can be observed. There is no limit to operation time. It is more compact than the rail-based system. The effort for using the mechanism is low.

5. DISCUSSION

The choice of the suspension concept depends on the priority of requirements. If handling aspects, such as unlimited duration operations, are crucial, mechanical suspension systems (rail-based or cable-driven) could be considered. These systems can be set up in a laboratory environment and provide a reliable possibility to test space robots during the development and qualification process without duration limitation. On the other hand, if a realistic zero-gravity environment is essential, neutral buoyancy and free-falling experiments could be considered. Realistic zero-gravity can be useful in gathering detailed measurements of how mechanical properties, such as friction change in zero-gravity compared to on-ground [8].

However, tests in a realistic zero-gravity environment using e.g. free-falling pose significant challenges and thus correspond to substantial drawbacks in the development process, namely short experiment duration, huge effort,

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[3] fulfilled because of zero-gravity

and excessive planning. Additionally, from the perspective of robot development, the utility of true zero-gravity is comparatively limited. In most cases, the mechanical loads on the robotic elements in zero gravity are much lower than during on-ground maneuvers due to the missing gravitational forces. This means that the setup for on-ground experiments could focus less on realistic zero-gravity environment and more on geometric flexibility, dynamic analysis capability, and usability. In combination with zero-gravity multi-body simulations, this could be a promising approach for validation purposes. On-ground measurements could verify the mechanical parameters in the multi-body simulation while the simulation's results can be used for the zero-gravity evaluation, including controller stability and power consumption analysis. Nonetheless, it remains crucial that the joint torque loads are reduced for the experiments as most space robots cannot bear their weight under Earth's gravity. This guides us in the direction of using a mechanical suspension system, such as rail-based or cable-driven.

When it comes to the dynamics analysis capability, cable-driven suspension systems are the most promising. The high vibration bandwidth due to its low moving mass and high winch dynamics allows for the separation of the mechanical modes of the space robot from the influence of the suspension system. This forms a major advantage compared to Gantry crane-based mechanical suspension systems which suffer from a huge inertia.

6. CONCLUSIONS

This manuscript answers the explorative research question of which requirements are significant in the context of designing a suspension system for a space robot, and subsequently, which concept aligns most effectively with fulfilling these requirements. As a first step, the literature review presents the most typical concepts for this purpose: Planar air bearings, helium balloons, neutral buoyancy, free-fall/parabolic flights, rail-based suspension systems, and cable-driven suspension systems. The requirement elicitation reveals the most important aspects of gravity compensation, geometric flexibility, dynamics analysis capability, and usability. In a comparative study, the concepts are evaluated concerning the stated requirements.

The discussion highlights that a pure zero-gravity setting holds relatively less significance in the context of space robot development and validation. What holds greater import is a suspension system facilitating 6-DoF movements, enabling dynamics analysis, and ensuring optimal usability. Guided by these criteria, the survey concludes that a cable-driven parallel robot offers the most desirable attributes for serving as a space robot suspension system. This concept not only enables arbitrary motions but also features a high dynamics in motion facilitating a dynamics analysis of the coupled system.

Future work will propose a detailed design of such a system including setup and experimental results. Furthermore, a control system needs to be designed. Apart from that, other concepts based on a different set of requirements might lead to promising approaches, such as extending an air bearing setup with additional DoF to overcome the 2D limitation.

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