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Compliant mechanisms for dust mitigation in Lunar hardware development: technology and material considerations

D H Budzyn[1], H Zare-Behtash[1], A Cowley[2] and A Cammarano[1]

[1] University of Glasgow, G12 8QQ Glasgow, United Kingdom
[2] European Astronaut Centre - ESA, Linder Hoehe, 51147 Köln, Germany

d.budzyn.1@research.gla.ac.uk

Abstract. During the Apollo missions, astronauts observed negative impact of Lunar dust on the surface hardware. The characteristics of Lunar environment and the regolith properties accelerate the contamination and promote the abrasion and clogging of different components in the equipment. To protect the hardware from damages in the future Lunar missions, several mitigation technologies must be adapted. In this work, we propose to consider application of solutions that are naturally dust resilient. Such solutions, called implicit dust mitigation technologies, include usage of compliant mechanisms. Compliant mechanisms use elastic deformation to achieve motion and can replace rigid-body mechanisms that suffer increased friction and jamming due to dust accumulation in the inter-element gaps. Material selection for compliant mechanisms needs to be considered very early in the design process, and as demonstrated in our work, it is crucial to the final mechanism performance.

1. Introduction

Apollo astronauts reported multiple dust-induced problems, which were classified by Gaier [1]. All recorded problems fall into one of the following categories: dust coating and contamination, seal failures, abrasion, clogging of the mechanisms, thermal control problems, false instrument readings, loss of traction, inhalation and irritation, vision obstruction. The range of the problems is very broad and therefore multiple dust mitigation strategies should be developed for the future Lunar exploration [2]. Furthermore, understanding of the Lunar environment and dust characteristics can help to identify useful mitigation strategies.

Our Moon does not have atmosphere or magnetosphere that could protect it from the solar wind plasma, UV rays and X-rays [3]. As a result, exposed Lunar surface develops electrostatic charge on its surface [4–6]. The electrostatic potential changes with the day-night Lunar cycle [7]. Such electrostatic behaviour enhances the adhesion of Lunar dust particles to surfaces of scientific hardware and makes it hard to clean. The difference of potentials is dependent on the work function of materials used in the equipment as compared to work function of Lunar regolith [8]. Furthermore, Lunar regolith has very wide distribution of particle sizes, with the smallest grains at around 2μm [9]. Such small particles can easily penetrate the gaps in rigid-body mechanisms as well as the gaps in the woven fabrics of spacesuit outer layers. The grains have sharp edges [10] and are made of minerals with hardness that often exceeds the hardness of 6 and above on the Mohs scale [11] – this is higher value as compared to hardness of frequently used engineering materials that build the elements of

Lunar hardware. As a result, Lunar dust particles are abrasive agents that can cut through fabrics and seals and etch equipment surfaces.

In this work, we focus on rigid-body mechanisms dust protection. Rigid body mechanisms (e.g., hinges, sliders etc.) are built with multiple components, that have gaps in between them. Those gaps can get penetrated by the Lunar dust which increases the internal friction of the mechanisms and can ultimately lead to jamming. There are multiple strategies to deal with the dust exposure and contamination [4,12]. Most of them belong to one of the following categories: active dust mitigation that uses external force to clean off the dust (mechanical, fluidal, electrodynamic etc.) and passive dust mitigation which mitigates the dust attraction without the use of external forces (coatings, modified surfaces, seals etc.). Another approach is to design hardware in a way that it is naturally dust resilient. In this work we focus on solving the problem of rigid-body mechanisms getting damaged by dust. The root cause of the problem is dust particles penetrating the inter-element gaps of mechanisms and clogging them [10]. As such, designing mechanisms without those gaps would create naturally dust resilient solutions – implicit dust mitigation. Compliant mechanisms can perform their kinematic functions, without the need of inter-element gaps providing capability to mitigate the dust impact on the hardware at the design level. In this work we explore the intricate relations existing between design, material and performance of compliant mechanisms, highlighting some key aspects that need to be considered in the material selection.

2. Implicit dust mitigation: compliant mechanisms

Compliant mechanisms are mechanisms that use flexible deformation to achieve motion [13]. As such they move without inter-element friction and do not require lubrication and planning for tribological wear [14]. The lack of tribological surfaces in contact with Lunar dust makes compliant mechanisms suitable solution to avoid the dust damage in moving components. Furthermore, compliant mechanisms can be constructed as monolithic pieces which can speed up manufacturing and assembly process as compared to rigid-body mechanisms. Compliant mechanisms deform elastically which also means they store elastic (strain) energy [15]. As such after the removal of input force compliant mechanisms spring back to their original shapes – this is behaviour that is desirable in multiple hold down and release mechanisms in the space industry. Compliant mechanisms have also some disadvantages, including limited motion range (due to elastic range of the deformation), non-linear effects with big displacements, non-intuitive design methodology and challenging loading conditions for some materials (e.g., polymers being susceptible to creep and stress relaxation). Nonetheless, the advantages and natural dust resilient make compliant mechanisms interesting candidates to be used in the Lunar hardware.

3. Compliant mechanisms synthesis

As already mentioned, compliant mechanisms can be less intuitive to design than rigid body mechanisms and the material selection usually poses a challenge, even though there is a wide range of materials applicable for compliant mechanisms. The sections below provide some discussion about those topics.

3.1. Design methodologies

There are multiple methods used to synthesize compliant mechanisms. They are divided into two main categories: analytical design and topology optimisation [14,16]. Analytical methods usually use a library of compliant kinematic pairs or building blocks that fulfil a certain kinematic function. Combination of those elements yields the final design, and from the designer point of view this method resembles the design of more traditional mechanisms. Topology optimisation is a design method that searches for optimum material distribution for a given problem defined by boundary conditions, objective function, and optimisation constraints. This method is popular in the design of static structures. For compliant mechanisms design the definition of objective function is still an open research question and there are multiple formulations that support the synthesis of compliant mechanisms [17].

Adjusting the stiffness of a compliant mechanism can be done in few ways. First one is to change the topology – e.g., instead of using one slender beam as a flexure two beams can be used to increase the stiffness. Next method changes the geometry – increasing the thickness of the flexure leads to higher stiffness. Another method is the change of material – for a given geometry of a flexure usage of material with lower Young's modulus will result in bigger deflections under lower stress.

3.2. Material selection

Selection of a material for compliant mechanism needs careful consideration, and as mentioned above it has big impact on the stiffness characteristic of a system. Furthermore, compliant mechanisms can present lumped compliance where the topology consist of structural (stiff) areas and flexible elements (flexures) that deform elastically. It is also possible to achieve distributed compliance, where most of the topology deforms elastically [16]. Nonetheless, the lumped compliance is more prominent in the field and the flexures (areas with most elastic deformation) are most prone to fatigue damage.

Polymers are generally susceptible to stress relaxation and therefore, for compliant mechanisms which might be required to remain in deformed configuration for extended periods, a plastic (permanent) deformation can occur even below yield stress. Another danger of using polymers is creep, that can plastically deform flexures under constant stress. Nevertheless, polymers are quite popular in consumer products which feature compliant mechanisms: flexible lids for cosmetic bottles, sealing clips, lids of food containers etc. One of the reasons for using polymers in these applications is their price but also high ratio of yield strength to Young's modulus. High yield strength means that the element can undergo higher stress before plastic deformation develops and low Young's modulus ensures higher range of flexible deformations. Metals are also suitable candidates for use in compliant mechanisms. They are considerably stiffer and therefore might require more force to achieve expected deformations but can offer good choice for precision applications. Another way to achieve bigger deformations, as already mentioned, is to change the geometry and therefore metal compliant mechanisms often present very thin long flexures that might be challenging to manufacture. As such, geometry, material, and manufacturing method selection need to be very closely considered together when designing compliant mechanisms.

3.3. Application examples

In this section the impact of material and design method on the performance of compliant gripper will be presented. Two design methods are demonstrated: topology optimisation utilizing a simple and versatile formulation from Koppen et al. [18] implemented in commercial software HyperWorks OptiStruct and analytical method utilizing the instant canter approach [19]. The grippers presented here are displacement driven; input displacement pushing on the input port results in the jaws of gripper closing. Furthermore, the grippers are prototypes, and the aim was to develop and manufacture them relatively quickly. Therefore, 3D printing Fused Filament Fabrication (FDM) was selected as a manufacturing method. In future space missions, 3D printing could allow manufacturing by astronauts in space to produce elements of hardware when needed. In this project, two different 3D printing materials were evaluated: Polyactic acid (PLA) and Thermoplastic Co-Polyester (TPC). Some representative values of mechanical properties of these materials are presented in Table 1. The exact values usually differ with the brand of filament, 3D printer used and multiple parameters like the orientation of specimen. Therefore, literature presents a range of the values differing from one publication to another [20–22]. Nevertheless, it is undeniable that PLA is stiffer than TPC, which will have impact on the resulting designs.

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Table 1. Selected mechanical properties of PLA and TPC.

	PLA **Polylactic acid**	**TPC** **Thermoplastic Co-Polyester**
Young's modulus [GPa]	3.8	0.029
Poisson's ratio	0.33	0.48
Elongation at Yield [%]	2	35

The first gripper design presented here utilises instant centre approach. This method works the same way regardless of material selected. It follows a few different steps to produce a sketch with desired topology, details on the method can be found in literature [19,23]. The drawing of produced topology is presented in Figure 1. As visible there are long flexures present in the design. The thinner the flexures the smaller stiffness they will have, and the width of 0.8 mm was selected here.

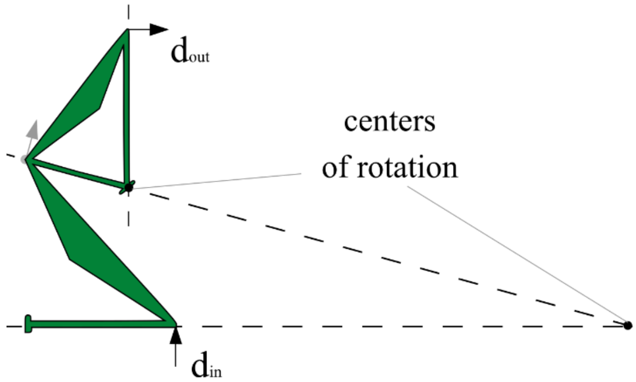

Figure 1. Half of the gripper conceptual design produced with instant centre approach method (analytical design).

The First gripper based on the design discussed above was printed using PLA. It is visible in Figure 2 in its original configuration and fully deformed state with closed jaws. The expected kinematic behaviour of closing induced by linear input force was achieved, and no problems concerning this gripper were noted.

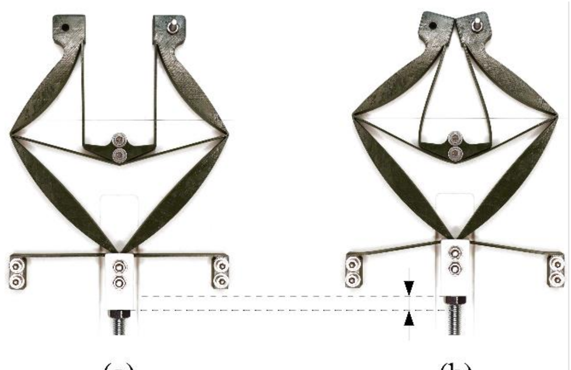

Figure 2. PLA 3D printed gripper based on the analytical design: (a) default position and (b) closed jaws position; dimension marked with arrows represent input displacement.

The same gripper topology (shape) was printed with TPC. This gripper is presented Figure 3. As already mentioned, TPC is more compliant material, and this has an impact on the behaviour of the gripper. It opens and closes as demonstrated in Figure 3 (a) and (b), but it differs from the PLA gripper when it comes to overall output stiffness. As demonstrated in the Figure 3 (c) it is possible to force the

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output to closed jaws position even though the input is fixed in the original (open) position. Such behaviour is characteristic of underconstrained compliant design, but this behaviour was not observed in the PLA gripper presented above.

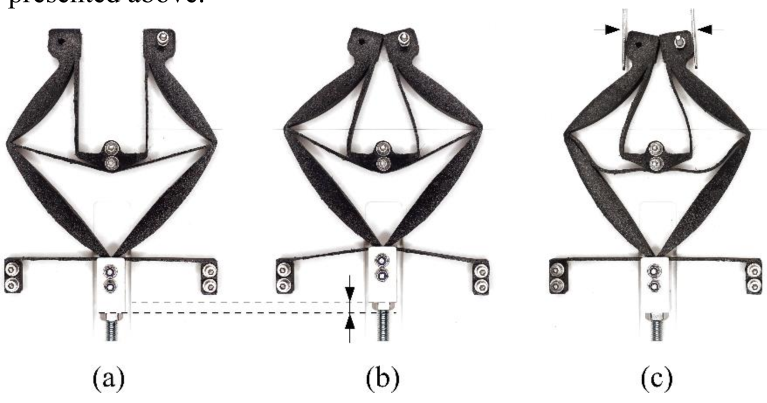

Figure 3. TPC 3D printed gripper based on the analytical design: (a) default position, (b) closed jaws position, (c) forced output closure with arrows demonstrating the external force; dimension marked with arrows (between (a) and (b)) represent input displacement.

The unexpected output behaviour is the result of the lack of appropriate stiffness of the flexures. Flexures provide degrees of freedom (DOFs), but they also provide degrees of constraint (DOCs) – Figure 4 demonstrates the theoretical DOFs and DOCs for a flexure that was used in the discussed gripper. More information about accessing the DOFs and DOCs for compliant elements can be found in the literature[24–26]. Here the problematic DOC is the longitudinal one. As visible in the Figure 3 (c) the flexures buckle with minimal force at the output. This lack of stiffness (as compared to PLA design) results from the application of TPC with the giver geometry (mainly width) of flexure.

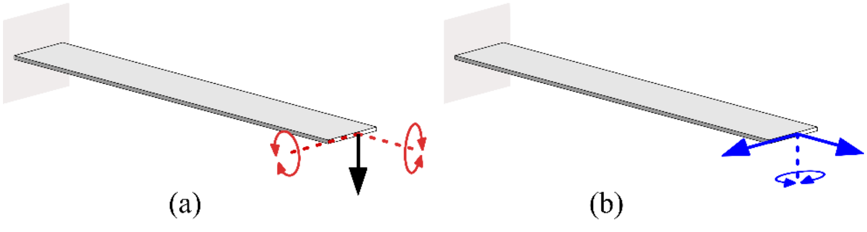

Figure 4. Flexure (a) degrees of freedom (DOFs), (b) degrees of constrained.

Topology optimisation of the next grippers was performed in commercial software HyperWorks utilizing the displacement driven ‘simple and versatile topology optimisation formulation for flexure syntheses’ developed by Koppen et al. [18]. This formulation was adapted to use for the gripper design, the representative selected iterations of optimisation are presented in Figure 5. Simulation was set up for maximum of 100 iterations but here it reached the convergence after 50 iterations. Half of the design domain was modelled assuming gripper’s symmetry. As visible in the last step, most of the intermediate densities (yellow and green elements) are removed from the design domain leaving an almost binary design (red and blue). In post processing all elements with densities below 0.75 were removed and the design was finalised to be 3D printed.

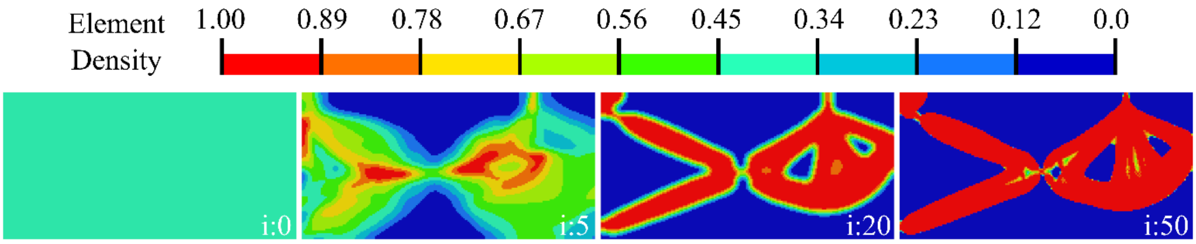

Figure 5. Topology optimisation progression for TPC compliant gripper; ‘i’ – number of iterations.

Figure 6 presents TPC 3D printed gripper in its default and deflected state. As visible, the gripper has expected kinematic behaviour – pushing on the input force closes the jaws. No problems were noted with this design and material combination.

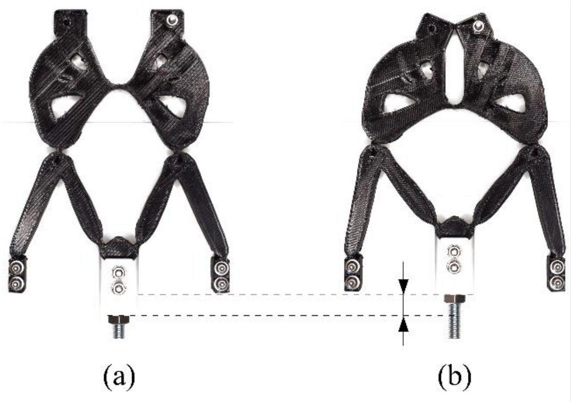

Figure 6. TPC 3D printed gripper based on the analytical design: (a) default position and (b) closed jaws position; dimension marked with arrows represent input displacement.

Topology optimisation was also performed for PLA gripper. As compared with the previous optimisation, the only change in the simulation was the material. Figure 7 shows the evolution of the topology. Even though this optimisation used more iterations, the green intermediate densities are still visible in the last step (i:100). To have continuous material in the design domain the densities above 0.35 were kept (which means they were shifter to density of 1). This number is much lower than for the TPC topology optimized design. It is important to note that the formulation used for the optimisation has a constrained on the global stiffness/compliance and both topology optimisation simulations (TPC and PLA) had exactly same constraints. As lower densities will make it to the final PLA design, it is evident that this design will exhibit higher stiffness.

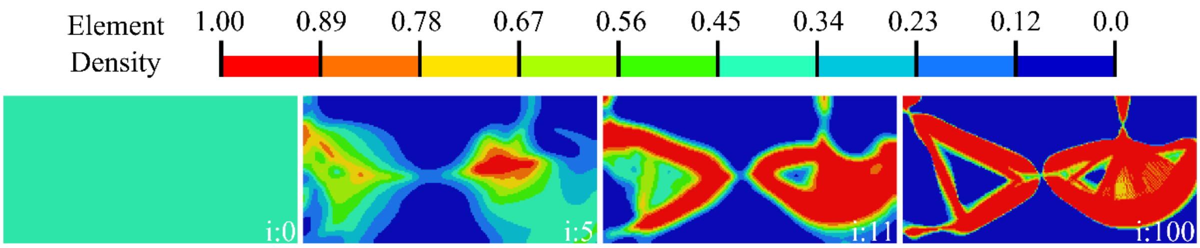

Figure 7. Topology optimisation progression for PLA compliant gripper; ‘i’ – number of iterations.

3D printed PLA gripper is presented in the Figure 8 in its default and deflected position. The deflection presented is very small since FEM analysis (Figure 8 (c)) show excessive stress occurring in the localised compliant hinge produced by the topology optimisation. To avoid damage of the hinge only small displacements induced performed. It is worth noting that adjusting the topology optimisation parameters or performing additional shape optimisation could immensely improve this design, but the scope of this paper is to show the impact of material selection combined with the design methodology.

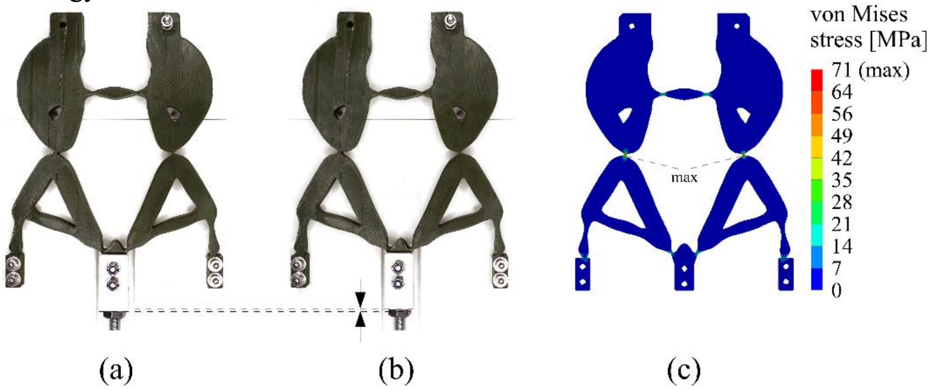

Figure 8. TPC 3D printed gripper based on the analytical design: (a) default position, (b) closed jaws position, (c) forced output closure with arrows demonstrating the external force; dimension marked with arrows (between (a) and (b)) represent input displacement.

4. Discussion

Lunar dust posed challenges in Apollo exploration operations and an effort should be made to mitigate its hardware impact in the future. No single dust mitigation solution will be capable of protecting all types of systems. Therefore, development of different approaches that can work together is crucial. One of the solutions to this problem is the usage of naturally dust resilient compliant mechanisms. As outlined in this work, complaint mechanisms have significant advantages in the Lunar environment. They also bring some design challenges, some of which were discussed in this paper.

We explored two different design approaches and two materials for 3D printing of compliant mechanisms. Topology optimized TPC gripper and analytically design PLA gripper exhibited satisfactory kinematic behaviour. As opposed to that, TPC analytically designed gripper failed in providing enough DOCs in the flexures, resulting in flexures buckling and gripper displaying underconnstrained behaviour. The PLA topology optimisation also led to unsatisfactory solution with high stiffness, and as demonstrated, the desired displacements cannot be supported by the flexural hinges present in this design. This shows that selection of the material and design have considerable impact on the final performance and should be selected simultaneously. The authors acknowledge that the materials presented here would not be suitable for the Lunar use. Nonetheless, there are materials (PEEK, PEKK) suitable for 3D printing that could be included in the hardware on the Lunar surface. Future efforts should focus on finding a range of Moon-suitable materials that could fulfil different functions and work with different design methods for compliant mechanisms.

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