Hoverboards: smart focal plane positioners for adaptive optics ELTs

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ABSTRACT

The ability to simultaneously position 'large' payloads over the focal surface overcomes some of the potential barriers faced by ELTs in implementing multi-object adaptive optics. The Australian Astronomical Observatory is prototyping a new positioner capable of moving larger payloads than a typical Starbug (fiber positioners proposed for GMT). These devices, called Hoverboards, are currently capable of positioning payloads up to 3 kg over the focal surface. Hoverboards are platforms that utilize air pressure and vacuum forces to reposition with either two or more Starbugs, amplified piezo-actuators or stepper motors. Hoverboards facilitate fast field configuration times with simultaneous positioning and best utilization of the focal-plane with diversified payloads enabling multi-object surveys. Hoverboards could conceptually position compact deformable mirrors over the focal surface for implementing multi-object adaptive optics or as an imager for ground-layer adaptive optics. We report on the development of a low-cost Hoverboards prototype suitable for flat and curved focal-plane surfaces for the GMT and E-ELT.

Keywords: Hoverboards, Starbugs, Focal plane positioner, Deformable mirror, Adaptive Optics, E-ELT, GMT, MANIFEST, AAO

1. INTRODUCTION

Adaptive Optics (AO) [1] is an important component for each of the planned Extremely Large Telescopes (ELTs). The use of AO allows for the correction of the optical wavefront aberrations induced by the atmospheric turbulence. The AO vastly improves the image quality and hence the science capability of the ELTs. Further, efficiency gains for ELTs can be obtained by performing AO on more than one science object at a time. This is known as Multi-Object Adaptive Optics (MOAO) [2]. The technique requires multiple wavefront correction (WFC) devices deployed across focal surfaces covering large physical areas (compared to current 8-10m class telescopes). This requirement creates new challenges, such as the positioning of these wavefront correction devices to within the accuracy and time constraints. Minimizing the overall cost is an important factor for the feasibility of MOAO on ELTs.

In an attempt to solve these challenges of focal plane positioning of multiple wavefront correction devices for ELTs for MOAO, the Australian Astronomical Observatory (AAO) has been developing the new concept of Hoverboards. The AAO has already reported on the concept of miniature wavefront sensors (WFS) for ELTs or Starbug WFS [3, 10], see Figure 2. Hoverboards are the next generation robotic positioners that can move much heavier payloads than Starbugs [4]. Hoverboards can be described as compact, modular and versatile platforms for accurately moving heavy payloads of considerable size over large focal surfaces of ELTs. Hoverboards are can either position over flat or curved focal surfaces, as well as operate at different gravity vectors, ranging from upright to inverted. The design being scalable to different sizes (focal area).

The key application we propose for our Hoverboards is for future instrumentation of the GMT, see Figure 1. The Manifest instrument proposed by the AAO for the GMT could benefit from future technology upgrades including Hoverboards. This then allows the GMT to benefit from MOAO or large kilo-sized IFUs. We are also considering potential applications for the E-ELT, since Australia is now a member (since 2017) of the ESO Community.

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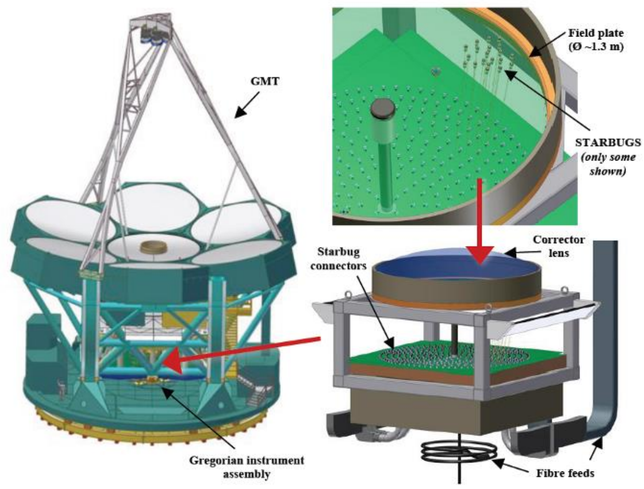
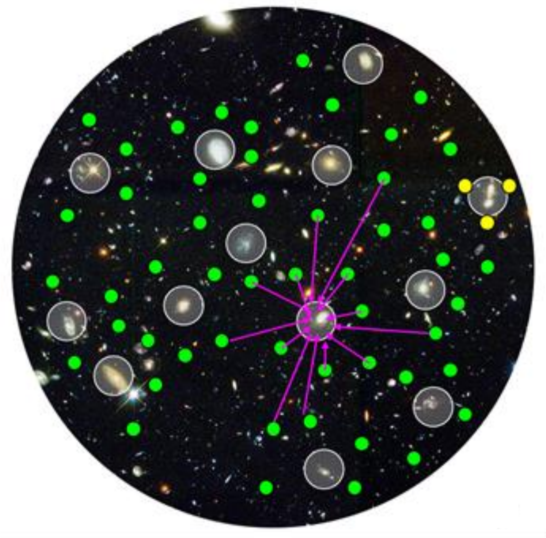


(a) GMT and MANIFEST (Starbugs positioner)



(b) Hoverboards with deformable mirrors (circles on galaxies) surrounded by Starbugs mini-WFS (green dots) for the implementation of MOAO.

Figure 1: Hoverboard applications for the GMT include MOAO, e.g. a possible upgrade option for MANIFEST [3, 7, 8].

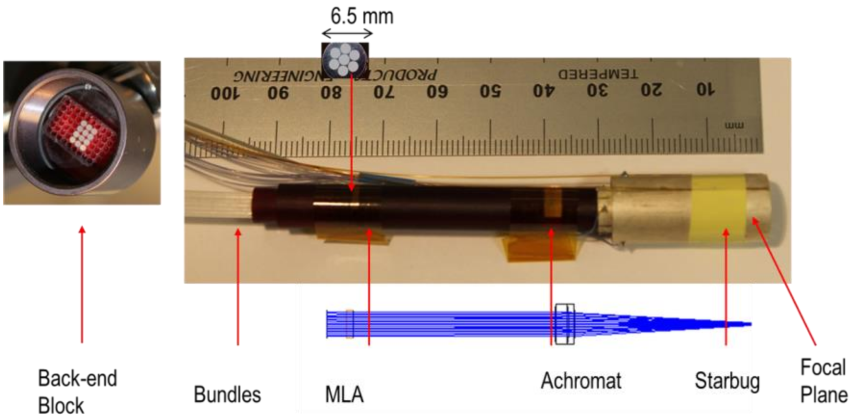


Figure 2: Starbug WFS's work well with Hoverboard DMs as the next generation positioners for MOAO. Shown is a prototype GMT version with 45x45 sub-aperture SH-WFS.

2. CONCEPT

The Hoverboards concept is shown in Figure 3. Hoverboards allow for the focal positioning of larger payloads than that typically possible with standard Starbugs. Hoverboards are smart focal plane devices that can be used over different focal plane curvatures as well position a variety of payload types (adaptive optics, large-format IFUs and imagers, see Section 3). Hoverboards could also be used to regularly clean optical surfaces in difficult to access locations. Hoverboards can be designed with battery power and communicate wirelessly, enabling autonomous operation and freedom to traverse over large focal planes (or mirror surfaces). We now consider the possible Hoverboard operational modes in reference to the GMT and E-ELT.

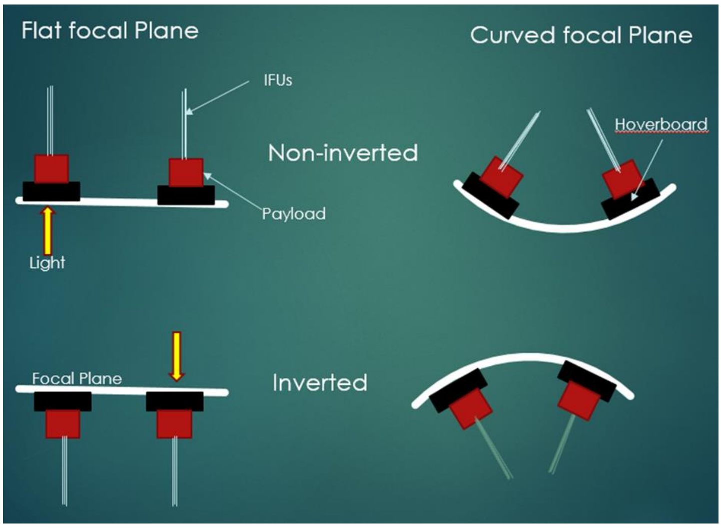


Figure 3: Hoverboard concept (see text) for flat and curved focal planes with gravity vector in the non-inverted and inverted positions. The black object is the hoverboard, and the red object is the payload. The white surface is the curved focal plane (glass). In this case the payload is connected to a fiber Integrated Field Unit (IFU). The diagram shows a pair of Hoverboards for multi-object operation.

For the GMT we propose two modes of operation: inverted and non-inverted as shown for the curved field plate in Figure 1 and Figure 3 (right). The inverted mode is the observational mode and the non-inverted mode is the positioning mode. The focal surface has a radius of curvature over 3m and a diameter approx. 1.25m. The non-inverted mode is required for positioning to allow the 'hover' effect where positive air pressure reduces the surface friction allowing the movement of heavy payloads based on the drive mechanism. The non-inverted mode is also a stable fail-safe configuration as the devices cannot fall from the field plate during the positioning. After positioning, a vacuum 'locks' the Hoverboard to the field plate which is then rotated to the inverted mode for the field observation. The vacuum holding force is typically several times that of the payload weight for a suitable safety margin to prevent dislodgement. The operation of the hover and vacuum in the non-inverted and inverted modes are illustrated in Figure 4.

For the E-ELT, the concept is similar to that of the GMT except that the Hoverboard operates over a larger diameter field plate (more than 3m) being of flat surface geometry in the non-inverted mode, see Figure 3 (top left). A suitable location on the E-ELT being the Gravity Invariant Focal Station (GIFS) below the Nasmyth B platform. However, as the GIFS is no longer in the E-ELT Construction proposal, it could be readily adapted to operation for the Nasmyth platform.

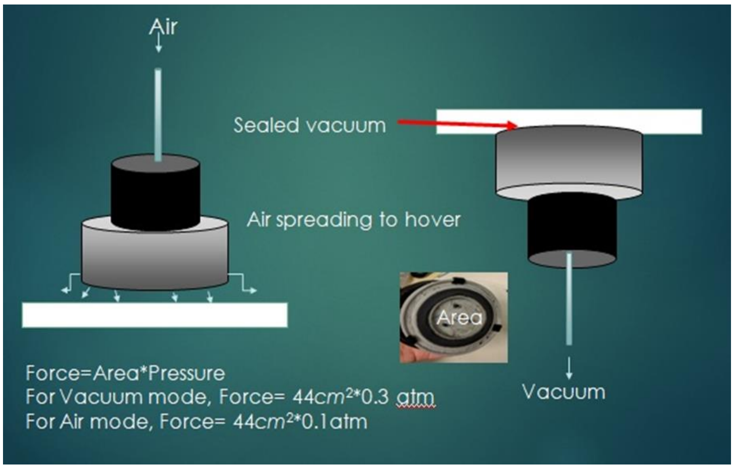


Figure 4: Hoverboard: showing the two modes of operation: inverted and non inverted with the vacuum and air respectively. The equations behind the forces are shown. The vacuum is sealed by a rubber washer.

A number of drive mechanism types are possible for the Hoverboard. We have successfully demonstrated Hoverboard positioning with several types of drive mechanisms (see Section 4), the first using Starbugs [4, 5], secondly amplified piezo-stacks, and currently using stepper motors. Starbugs are currently (Oct 2017) being commissioned for the TAIPAN [6] instrument (see Figure 5) for the UKST and are proposed for the MANIFEST [7, 8] instrument for the GMT. Starbugs provide positional accuracy (up to 1-2 microns) but typically have low speeds (1-2 mm/sec). The use of amplified piezo-stacks provides the ability to increase the 'step' size and movement force compared to Starbugs. The use of stepper motors have the advantages of both speed and torque (with gearbox), allowing positioning over large surfaces and small inclination angles (field edges on curved surfaces). However, with stepper motors there are issues with coarser positional accuracy, requiring either gearbox or micro-stepping control.

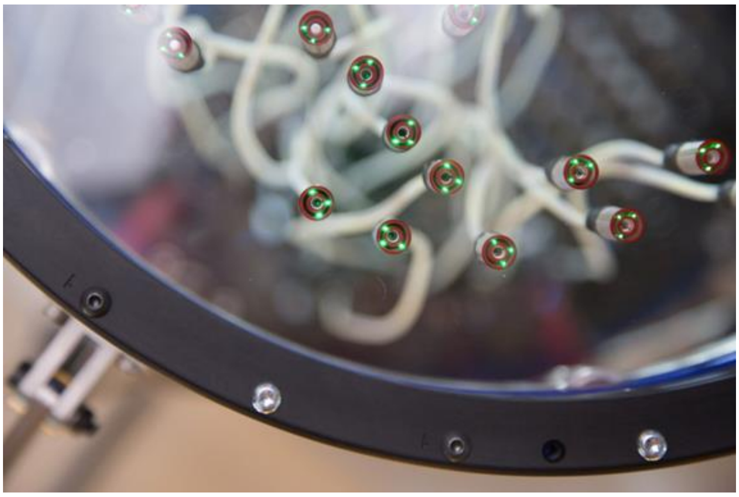
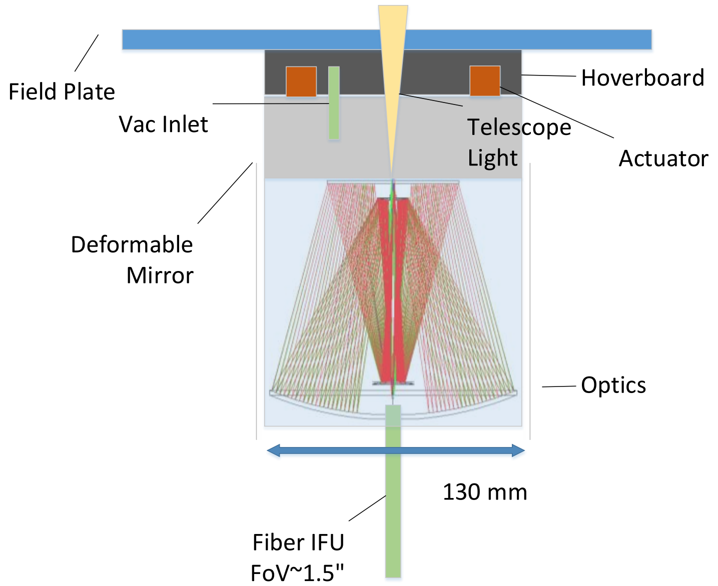


Figure 5: Starbugs for the TAIPAN instrument. Starbugs are suitable drive mechanism option for Hoverboards.

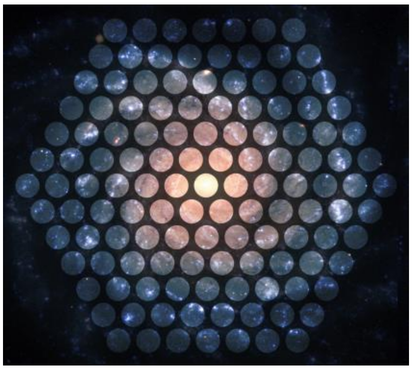
3. PAYLOAD TYPES

The Hoverboard has the potential to carry a variety of payloads. For example, payloads could be deformable mirrors, wavefront sensors, IFUs, or the combination of those three components. The Hoverboard payload is limited by the total weight and volume restrictions. The current prototype has been demonstrated in the lab for positioning a payload of weight 3 kg. For the GMT, we propose several potential payloads, a deformable mirror, large format fiber-IFU and ground-layer AO (GLAO) [9] imager, see Figure 6 and Figure 7.

The use of deformable mirror payload could enable a MOAO facility for the GMT, see Figure 1. Hoverboards could also have a camera payload for multi-object GLAO imaging surveys over the 20+ arc-minute field of the GMT, as shown in Figure 7. Hoverboards could also be part of maintenance and servicing with purposed payloads that regularly clean the optical surfaces in locations considered difficult or hazardous for manual cleaning. These payloads applications could be equally be scaled up to the larger E-ELT.



(a) GMT Hoverboard concept showing a deformable mirror plus several other mirror surfaces for compactness, with a 200+ fibre science IFU payload over 1.5" field as a MOAO 'unit'.



(b) Fiber IFUs capturing the image of a distant galaxy with 127 fibers (from MANGA Survey). Hoverboards could potentially carry a much larger 'unit', say 1000+ fiber IFU.

Figure 6: Payload types for Hoverboards suitable for the GMT, also scalable to the E-ELT.

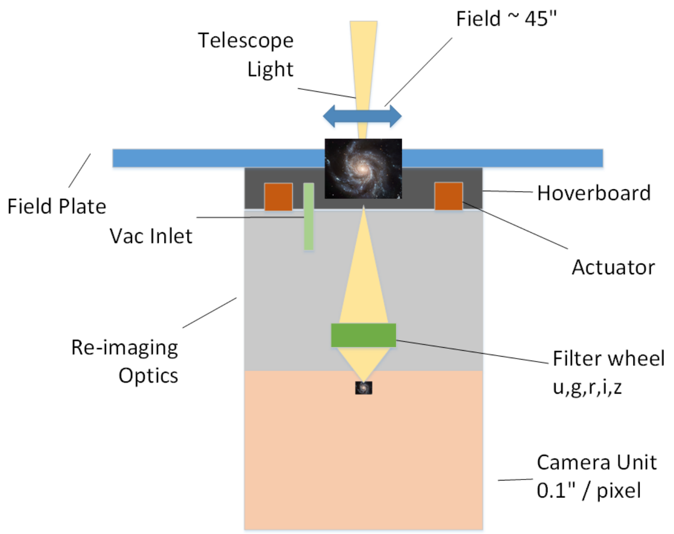


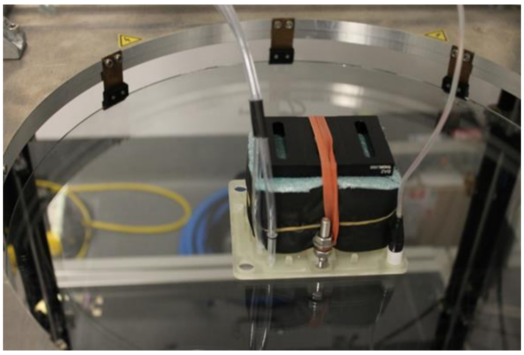
Figure 7: Hoverboards multi-object imaging 'unit' suitable for GMT GLAO.

4. PROTOTYPES

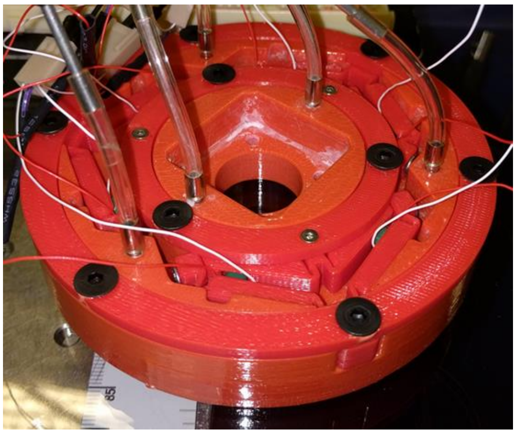
The AAO has already prototyped several Hoverboard designs, each with different objectives in mind. The two previous prototypes are labelled Type 1 and Type 2, are shown in Figure 8. The current prototype (Oct 2017) is Type 3 and shown in Figure 9. These prototypes have served as the research topics for several AAO student fellowship 12-week projects. The AAO student fellowship programme provides astronomical research and instrumentation opportunities to undergraduate students in science and engineering fields.

The Type 1 being the first prototype (early 2014), uses Starbugs to position a 750 grams payload over a flat focal surface in the non-inverted position, see Figure 3 (left). The payload was selected to model the weight and dimensions of an ALPAO DM97-15 we used for AO lab experiments and AO demonstrator on the 3.9m AAT [11]. Although a single Starbug was sufficient to position the payload, at least two Starbugs are needed for rotational stability, preventing any payload pivoting around the Starbug. The Type-1 prototype has been successfully demonstrated in the lab.

The Type 2 being the follow-up prototype (early 2017) with the goal to position in the inverted position at the field pointing (not possible with Type-1) to minimize downtime due to field configuration. The secondary goal being the support for payloads up to 2kg. The Type 2 was a first effort at a suitable design for a GMT Hoverboard. The concept uses two discs attached with the use of three custom designed amplified piezo actuators. The Type 2 is currently in the development and testing stage with further efforts required for a full working demonstration. However, we since have learned that it is a challenging goal for Type 2 to position against the strong clamping vacuum in the inverted position. The difficulty is also compounded by the payload weight when moving Hoverboard 'uphill'.



(a) Type 1: Hoverboard using Starbugs operating in the non-inverted position over a flat surface with payloads up to 750 grams.



(b) Type 2: GMT Hoverboard using amplified actuators with goal to operate in the inverted position at the field position with a payloads up to 2kg.

Figure 8: Previous prototypes of the Hoverboard

The Type 3 prototype is the latest (Aug 2017) and shown in Figure 9. Type 3 is an attempt to combine the characteristics of Type 1 and Type 2. The goal for Type 3 being to position in the non-inverted position with heavier payloads (up to 3kg), over curved (GMT) or flat (E-ELT) focal surfaces. Positioning in the non-inverted position reduces the problem difficulty by allowing the use of an air bearing to significantly reduce the payload surface friction. Also, Type 3 ability to move with higher speed and power allows it to work efficiently over the large curved focal surface of the GMT. The Type 3 operation in the inverted position (GMT observations) is achieved by applying a vacuum to lock device to the focal surface after positioning maneuvers and then rotating the field plate to the required field position.

The Type 3 prototype in Figure 9 is the first prototype to incorporate a battery and be controlled wirelessly over WiFi. This reduces the required physical cabling to the Hoverboard to include the air hose and science fibres (if applicable). For the prototype electronics, we used Arduino UNO WiFi controller interfaced with a stepper motor board. There is further scope down the track to optimize the electronics for compactness and robustness.

Aspects of the mechanical design for Type-3 are shown in Figure 10. The two main components of the chassis are the payload platform and drive modules, with a basic spring suspension joint linking both. The drive module includes the electronics with two small-sized stepper motors directly coupled to the wheels (also 3D printed). The payload platform makes use of mounts to secure test weights as well a large flat rubber washer underneath that seals the air chamber. The same air hose is used to supply positive air and vacuum pressure. The Velcro pads to make smooth contact with the surface when in the 'hover' positioning mode. The Type-3 prototype has also been successfully demonstrated in the lab by positioning a 3kg payload over a curved field plate (ROC similar to the GMT) in the 'hover' mode and then being inverted from 0 to 180 degrees in the 'vacuum' lock-down mode. Figure 11 shows a lab test where the Hoverboard is successfully holding a 3kg payload in the inverted position.

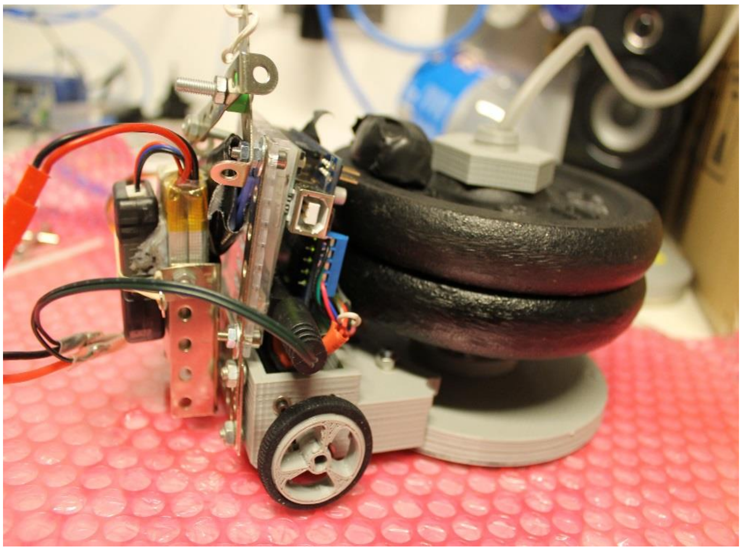


Figure 9: Type 3 prototype positioning a 3kg test payload.

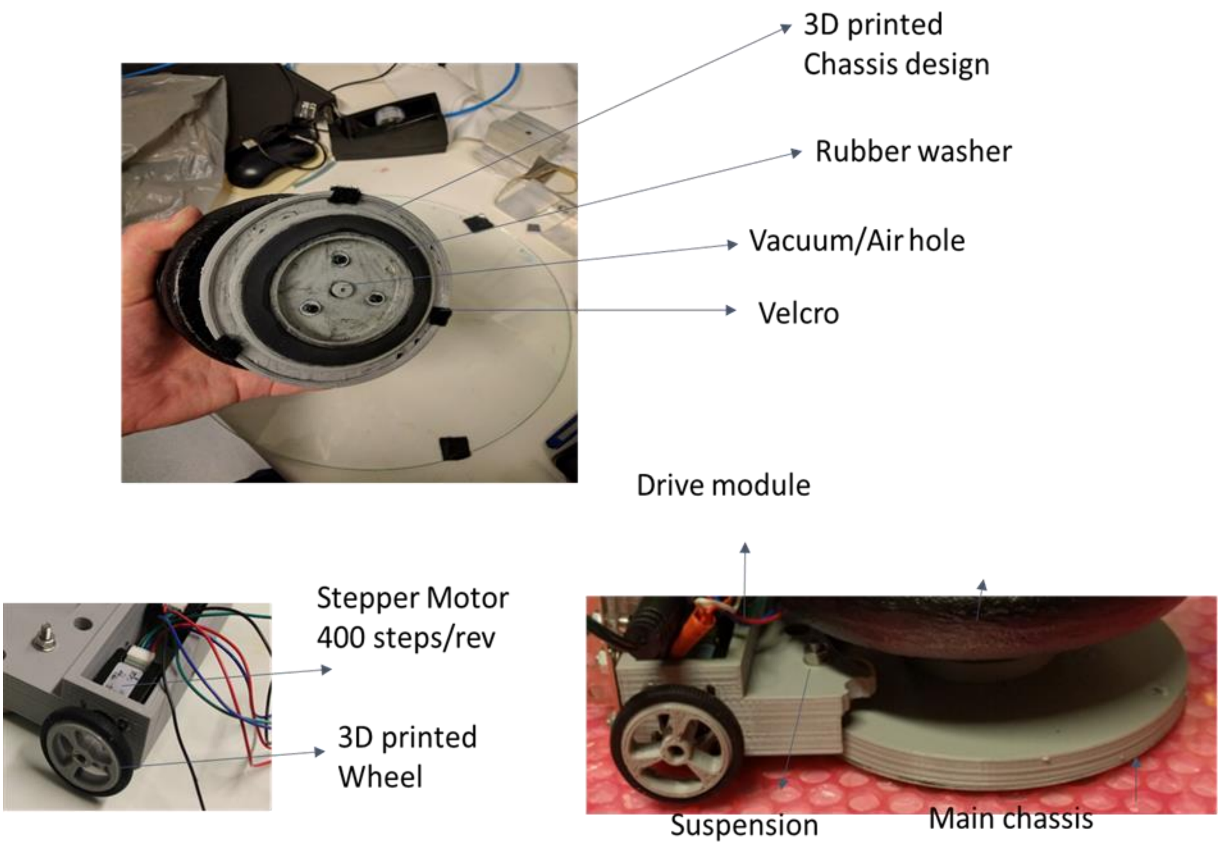


Figure 10: Mechanical design of the 3D stepper Hoverboard

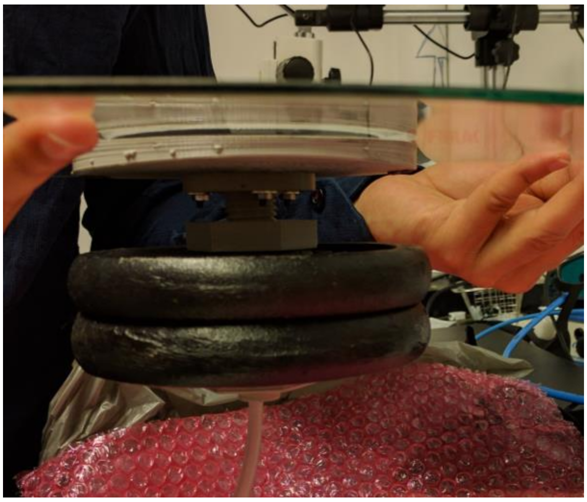


Figure 11:Hoverboard inverted test holding a 3kg payload.

5. CONCLUSION

In this paper we have proposed the 'Hoverboards' concept as a potential focal plane positioner for ELTs. Hoverboards solve many of the field configuration challenges that could be faced by ELTs with adaptive optics. Hoverboards provide simultaneous focal positioning of large payloads (experimental 3kg) over the large focal planes (up to 3m) with flat or curved surface geometry. This allows increased utilization of the focal plane area and the reduction in field configuration times compared to traditional pick-and-place robot positioners. Hoverboards have been prototyped and demonstrated to operate over flat or curved focal surfaces, as well as different gravity vectors. Hence the technology is transferrable to the GMT or E-ELT.

We have proposed several Hoverboard applications for the GMT that are also scalable to the E-ELT. Hoverboards payloads could include deformable mirrors for MOAO, large format fiber-IFUs and GLAO imaging devices. Hoverboards can also be assigned as cleaners of optical surfaces in locations that are not suitable for regular manual cleaning and maintenance. Therefore, Hoverboards enable convenient access to the focal plane for a wide variety of payloads to deliver the best science outcomes at minimal costs for ELTs.

We have presented several prototypes (Types 1-3) each with different design goals. We have successfully lab demonstrated prototype (Type 3) to move a 3kg payload over a flat and curved focal surface as well as operate in the inverted positioned (as required by GMT / MANIFEST). We have also demonstrated several types of drive mechanisms, including the use of Starbugs (Type 1). We have also demonstrated the use of battery power, micro-controller and wireless communications in attempt to make 'smart focal plane positioner' devices. Further work includes making these devices more compact and robust, development of new software control algorithms and metrology.

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