Proceedings of The Canadian Society for Mechanical Engineering International Congress 2016
2016 CCToMM M^3 Symposium
June 26-29, 2016, Kelowna, British Columbia, Canada

ATLAS MOTION PLATFORM: REDESIGN OF ACTUATION SYSTEM COMPONENTS

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Abstract— The Atlas motion platform is both the focus of a multi-year multi-disciplinary Carleton University fourth year capstone design project known as the Carleton University Simulator Project (CUSP), and that of a rich research enterprise. It is a unique motion platform used as a flight simulator that allows for unlimited rotation of a cockpit housed in a 9.5 foot diameter composite sphere about any axis driven by three mecanum wheels, in addition to three decoupled orthogonal translations provided by a translational motion stage. Because of the nature of the sphere motion the velocity level constraints are non-holonomic, meaning that they cannot be integrated to yield orientation level information. Hence, orientation level kinematics are managed with fused external optical and internal gyroscopic measurement systems. In this paper we discuss the current state of the actuation system, and manufacture-based issues that prevent the mecanum wheels from functioning as expected and how they have been addressed to enable the sphere to be rotated. In addition, we discuss the visual orientation system (VOS) and the internal orientation system (IOS). Orientation level control has been achieved with the fused VOS and IOS systems on a 4 foot diameter prototype, but it is not immediately obvious how to scale the measurement systems to the full-scale prototype. We discuss the design decisions that have been made to enable the VOS to be implemented on the full-scale 9.5 foot diameter sphere.

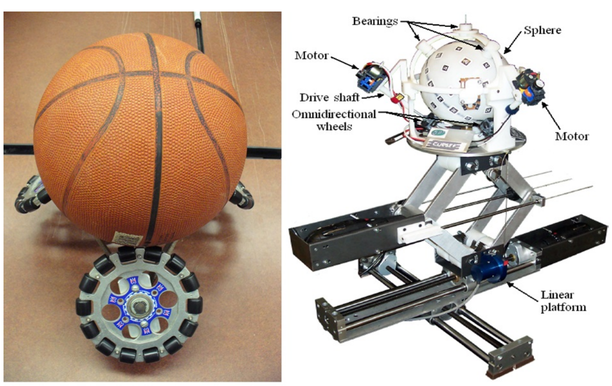
Keywords- Atlas motion platform; mecanum wheels; optical orientation estimation.

Figure 1. A 3D Rendering of the Atlas motion platform.

I. INTRODUCTION

The Carleton University Simulator Project (CUSP) is a fourth year capstone design project in mechanical and aerospace engineering fusing the work of undergraduate and graduate students. Unlike capstone design projects at most other universities, CUSP is run as a small design office with as many as 30 students led by three or four faculty members. The students experience working in a virtual enterprise environment. The ultimate goal of this design project is to address issues associated with conventional training simulators, which typically use the hexapod configuration to provide motion cues. While widely used, studies have shown that hexapods are incapable of producing the range of motion required to achieve high fidelity simulation required in many applications. For example, Gawron et al [1] determined, through studies addressing simulator effectiveness in training, that, based on a range of vehicle types and applications, high-fidelity simulation requires roll, pitch, and yaw angular displacement ranges in excess of 180°. These minimums are not achieved by most existing commercial motion bases. Recognizing the kinematic and dynamic shortcomings of the industry standard hexapod, CUSP was mandated in 2002 to identify conceptual motion platform designs that would overcome the hexapod's shortcomings, and have the appropriate kinematic architecture for as broad a range of vehicle types as possible. This has been accomplished, at least conceptually, by Atlas [2, 3], which was first introduced in 2005. The current conceptual model of the Atlas motion platform is illustrated in Figure 1. It permits unlimited angular displacements about any (every) axis through the geometric centre of the sphere. Moreover, Atlas decouples its three-dimensional translational workspace from its unbounded, singularity-free orientation workspace. In the current configuration, a MOOG MB-EP-6DOF Gough-Stewart platform [4, 5] is used to provide translation while Atlas provides the rotation. Hence, the entire reachable workspace of the motion platform is, by definition, completely dexterous: at any point in the reachable translation workspace of the MOOG platform, the sphere can have any orientation.

Over the course of the last decade, Atlas has evolved through two small-scale proof-of-concept models which used omnidirectional wheels, see Figure 2. However, studies conclusively showed that the amplitudes and periods of the induced vibrations caused by the offset castor roller races were too large, and that mecanum wheels should be used instead [6, 7, 8].



(a) (b)

Figure 2. Proof-of-concept models: (a) basketball demonstrator; (b) Atlas Lite.

Once proof-of-concept was satisfactorily demonstrated, manufacturing and materials questions needed to be investigated. The Atlas Technology Demonstrator Platform (TDP), shown in Figure 3, was designed and manufactured between 2006-2008. The sphere shell comprised eight identical flanged segments. Each flange between sphere segments was bound together with a series of bolts, while an aluminum reinforcement was applied to both sides of the joining flanges in order to provide additional stiffness to the sphere, as well as serving as a continuous washer for the bolts to prevent damage to the sphere flanges. In addition to these stiffeners, a series of ribs that serve as a mounting interface for the internal structures was also connected at a 90 degree angle to the flange stiffeners. This created a smooth 4 ft diameter sphere with exceptional motion characteristics [9].

Figure 3. Atlas TDP: 4 ft diameter composite prototype.

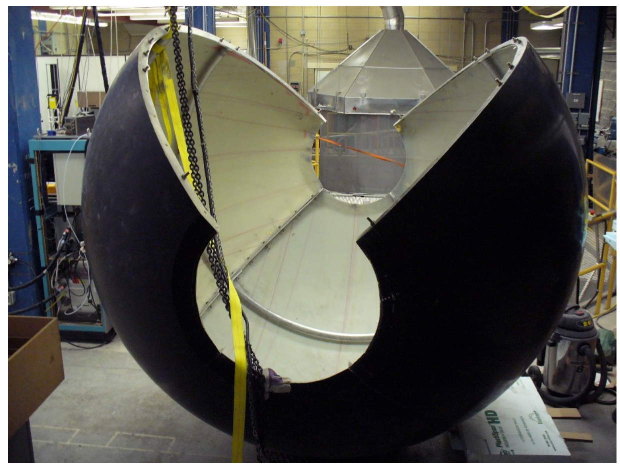


Figure 4. Atlas full-scale internal sphere structure.

Actuation and control strategies were developed using the TDP. The circular barcodes seen on the surface of the TDP in Figure 3 are used by the VOS to estimate sphere absolute orientation.

The Atlas full-scale prototype is housed in a 9.5 ft diameter fiberglass sphere, consisting of an internal support structure for increased rigidity based on that of the TDP, see Figure 4, as well as two hatches to facilitate entry and egress. Due to mechanical and spacial design constraints, the sphere shell has been designed to comprise four identical quarter spheres. Using epoxy and S-glass, the strength required to maintain integrity under the loading from the active mecanum wheels was achieved, with an estimated failure load in excess of 1000 psi. Referring to Figure 1, orientation activation is achieved with three active mecanum wheels, while sufficient normal force to mitigate slip between the active castor rollers and the sphere is supplied by an upper halo containing 12 passive mecanum wheels. The weight of the sphere and force supplied by the upper passive wheels is distributed among 12 lower passive mecanum wheels and the three active ones. The full scale platform in its

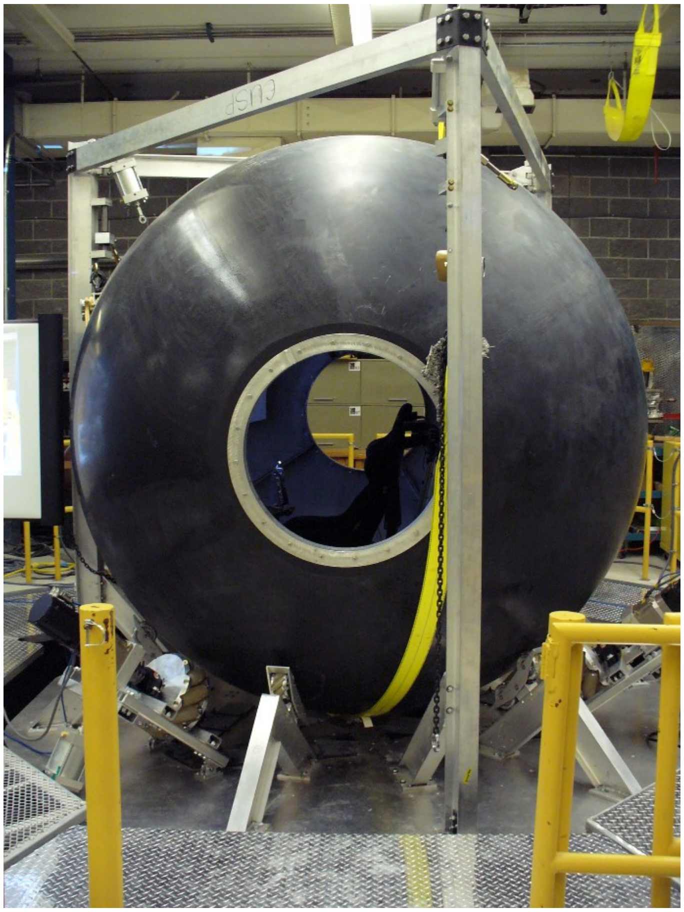


Figure 5. Atlas full-scale platform.

current state is shown in Figure 5.

This paper presents a discussion of actuation issues centred around the active and passive mecanum wheel castor rollers. The current rollers are 77A durometer polyurethane. However, they are not behaving as predicted, moreover, the injection moulding process left large random voids inside most of the rollers. Hence, new rollers of 85A durometer are scheduled to be manufactured with Delrin inserts which will act as axle bearing material. The insert selection study will be outlined.

Additionally, the sphere orientation control will rely on a fused measurement system combining the VOS and the IOS. The critical component of the VOS is the circular barcode markers affixed to the sphere surface. Hence, sphere barcode sizing and camera placement will be discussed.

II. Orientation Actuation System

Orientation actuation of Atlas is accomplished using three active mecanum wheels, which provides unbounded angular displacement of the sphere about any axis. The three wheels are each driven by three independent motors, and use 10 free spinning castor rollers which provide motive forces in the roller axial direction, and slip in all other directions to allow for tractive forces applied by the other two active wheels, see Figure 6.

Figure 6. Active mecanum wheels.

The Atlas sphere is constructed of a high strength fiberglass material: 12 plies of 24 oz S-glass cloth and PT 2712 epoxy resin. The lamination ratio was approximately 60:40 cloth to resin. The composite sphere has a maximum stress of 1000 psi and the polyurethane castor rollers of the mecanum wheels allow for sufficient surface contact on the Atlas surface avoiding load-induced damage. However, the first set of active rollers possessed a combination of voids and an insufficiently low durometer meaning that too much deflection occurs, preventing actuation of the sphere due to the resulting contact of the outer aluminum hubs of the mecanum wheels with the sphere. During the polyurethane injection moulding process, each original steel axle acted as a heat sink, quickly cooling the polyurethane and introducing voids in the rollers. To eliminate the voids a plastic insulating material was sought. Delrin was chosen for its high material strength, bearing capabilities, and low price. The Delrin insert offers reduction in the thickness of polyurethane, reducing voids during the injection moulding process and adding rigidity to the rollers. The higher durometer of 85A polyurethane combined with the Delrin inserts create a castor roller which provides a surface contact area of 2.5 in^2, which is required for load distribution.

In order for the three active mecanum wheels to provide torque input into the sphere, sufficient tractive force is required. The active wheel castor rollers and Atlas fiberglass interface require a tractive force of 1500 lb_f to avoid loss of traction [10]. Pneumatic actuators are connected to each active mecanum wheel to supply the required normal force to each wheel. To counter the upward force from the active wheels, a halo ring containing 12 passive mecanum wheels with 77A durometer polyurethane rollers at equally spaced intervals will rest on top of the sphere, attached to three pneumatic actuators to supply the appropriate downward force. These passive wheels are smaller than the active wheels, see Figure 7.

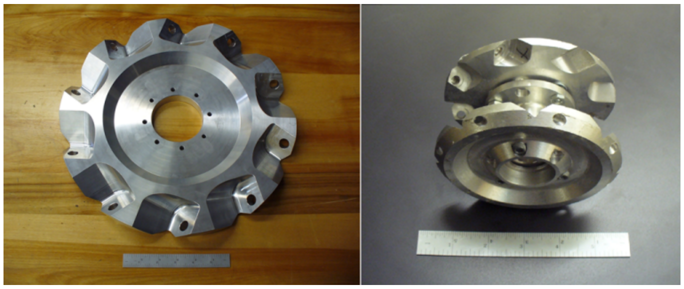


Figure 7. Active mecanum wheels, left; passive mecanum wheels, right.

The original caster rollers for the passive mecanum wheels were injection moulded, similar to the active wheels, onto steel axles. The knurling in the steel axles was insufficient, causing delamination in the polyurethane. The current design allows the axle to spin in brass bushings. However, the original axles could fail under the applied load after testing in a hydraulic press under specific loading conditions, thus larger diameter axles were required. Increasing the axle diameter eliminates space for the brass bushing; the steel axle is now be fixed to the outer aluminum hubs. The castor rollers are injection moulded onto teflon inserts, which act as a bushing to spin about the relatively fixed axle and ensure no delamination occurs. Teflon was chosen over Delrin for the passive wheels due to its higher melting temperature, decreasing the chance of melting during the injection moulding process. In addition to the 12 upper passive wheels, 12 lower passive wheels are used to distribute the static weight and dynamic loads applied to the Atlas sphere by the upper passive wheels. These wheels are designed to the same load specifications as the upper passive wheels.

III. Orientation Measurement System

Facilitating a singularity free, fully dexterous orientation workspace for Atlas presents difficulties not typically seen for orientation and position sensing systems; specifically, the orientation is unbounded about any axis. Tracking the orientation is accomplished using a tri-axial magnetic gyroscope and three orthogonal accelerometers about the same axes which comprises the internal orientation system (IOS) mounted near the centre of the sphere. However, as with all magnetic gyroscopes, the IOS signal drifts in a non-deterministic manner, therefore the drift can not be filtered out of the orientation estimate.

Increasing the fidelity of the orientation measurement system in order to provide accurate orientation level control requires an additional external orientation measurement system to mitigate the effects of drift of the IOS. While this requirement is not, in and of itself, problematic, it adds complexity due to the fact that the pilot of the simulator is completely occluded from view due to the nature of the sphere itself, and thus nothing internal to the sphere will accomplish the increased orientation fidelity. Necessarily, this implies that the absolute orientation of the sphere must be tracked from an external, fixed point in space. This external vision-based system is the visual orientation system (VOS). The internal IOS and external VOS signals are fused using an unscented Kalman filter yielding orientation estimates at approximately 60 Hz for the Atlas TDP. However, the aim here is not to discuss the fusion, rather the bar code identification of the VOS on the full scale Atlas.

A. *Visual Orientation System (VOS)*

The VOS relies on a relatively fixed camera that moves with the MOOG motion platform, and external markers that function as bar codes. On the Atlas TDP, each of the 128 markers is coded into a database used to define where each marker is located on the outside of the sphere using an Optotrack measurement system, and has that position designation mapped to the centre of each bar code marker. Figure 8 illustrates the view of the camera on the Atlas TDP.

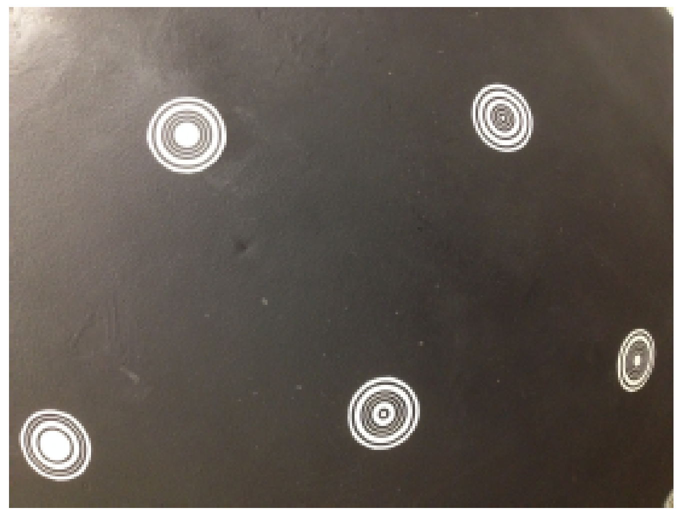


Figure 8. Atlas TDP VOS bar code markers.

Photogrammetric acquisition of orientation data is an inherently powerful tool, given adequate computational power. However, the operation of the VOS itself requires several interstitial image processing steps in order to provide an image that is clear enough for the processing suite to recognize the orientation information contained within the image. Initially, the image from the VOS capture camera is read into a LabVIEW suite which performs the operations required for the VOS to function. For ease of use, and clarity of results, a live stream version of the image is displayed in what is referred to as the VOS front panel, shown in Figure 9. This front panel contains a host of information about the location, both relative and absolute, of the markers which are detected by the VOS algorithms.

While the front panel affords the user a large array of data that is computed by the underlying algorithm, it does not afford an opportunity to perceive the work that is being done behind the scenes by the algorithm itself. Upon initial read in of the data, the image is converted from a full colour image into a U8 Grey Scaled format. While this grey scaled format allows the system

Figure 9. Atlas TDP VOS front panel during operation.

to easily recognize the barcodes, it requires that the sphere be well illuminated throughout operation. Problematically, this illumination necessarily creates glare on the sphere, which, while it does not obscure the barcodes themselves, creates distortions and artifacts within the image. This entails that the coating of the sphere be made from a matte finish, in order to mitigate the affect of the glare on the performance of the VOS as a whole. Once the grey scaled image has been acquired, it undergoes a process known as blob analysis. Through this analysis, the VOS algorithm recognizes the sizes of blobs within the image; these blobs are any light coloured area within the image. Threshold values allow the VOS to then filter out unnecessary blobs, narrowing down the perceived light patches, based on size. Light patches which correspond to actual markers, and are not artifacts of the glare on the sphere are left at the end of this process.

Due to the nature of using a two dimensional marker on the surface of the sphere, and subsequent observation and processing, the circularity of the observed markers is distorted within the camera plane. Subsequently, each of the remaining blobs has a centre point defined within the frame viewed by the camera, while also measuring the maximum height and width of these blobs. From the measurements of the blobs, the VOS algorithm uses the observed major and minor axes to locate the central point of each marker. From this defined centre point, the VOS can define exactly how each marker has been translated within the frame of view, relative to their absolute orientation on the outside of the stationary sphere geometric model, and known dimensions of the markers. Using the known spacing between each marker band within the barcode as a guide line, this portion of the algorithm fits a projected and scaled series of identifying points to each barcode within the view of the camera, illustrated in Figure 10.

Once fitted to the image, the identifying points are used to track high and low light inputs and therefore identify the binary code which corresponds to each individual marker. From this data, a marker location data base is used to determine the corresponding sphere surface position. Once the sphere surface position data that corresponds to each marker has been obtained, the VOS then uses the previously defined marker centres to

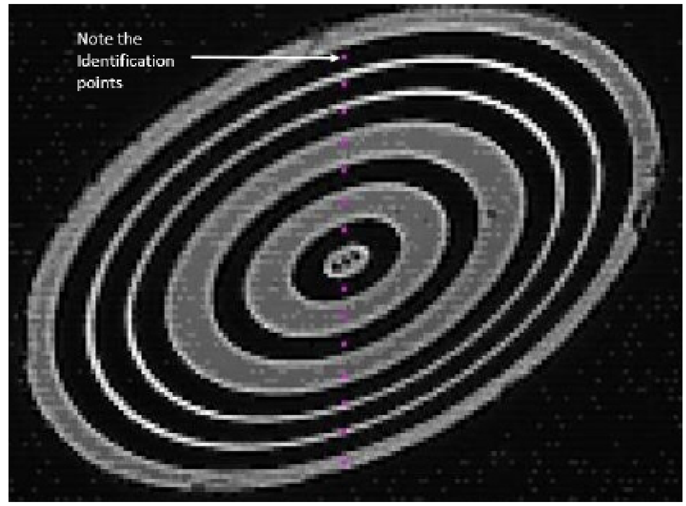


Figure 10. Atlas VOS processed marker image, with barcode identification points.

obtain the absolute orientation of the sphere. At minimum, the VOS requires the recognition of two bar codes in order to provide the system with an accurate estimate of the sphere orientation. However, due to the deformable nature of the full sized fiberglass shell, recognition of more than two barcodes is desirable in order to reduce possible errors. While these steps enable orientation control of the Atlas TDP to a precision of one tenth of a degree [11], scaling the VOS for use in the full scale Atlas prototype is inherently nontrivial. Creating the VOS was a phenomenological process which required a large amount of testing and calibration. However, owing to documentation created by past CUSP students, the majority of these testing and calibration processes are archived, and are expected to be reproducible in the final product.

Though the systemic functionality will remain the same, scaling the VOS from the Atlas TDP to the full scale Atlas requires careful consideration of the marker size, placement density, and material properties. Marker size is primarily a function of the capture rate of the camera, and the surface velocity of the sphere. While the angular rates achieved on the Atlas TDP are similar to those for which the full scale prototype is designed, the absolute magnitude of the surface velocity increases dramatically after scaling, illustrated in Figure 11.

Scaling the band dimensions of the markers facilitates the acquisition of the barcode value without the effects of motion blur being present, though the barcodes can not be scaled dramatically, as this would result in a loss in the required marker density for the proper definition of the absolute orientation of sphere. Incorporating the increased size of the markers onto the sphere will require alterations to the initial VOS code, and due to the increased surface area of the sphere, depending on the marker size the number of markers will need to be increased from the 128 used on the Atlas TDP in order to allow for at least two markers to be within the field of view of the camera.

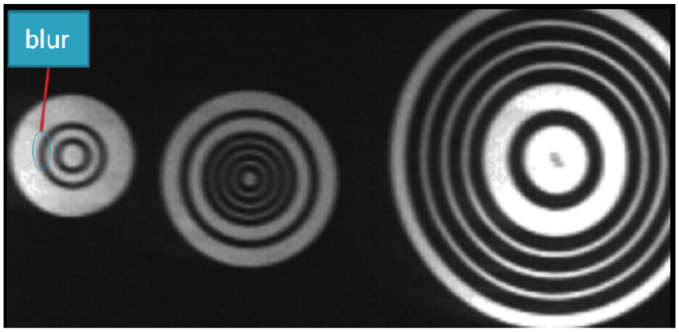


Figure 11. Atlas VOS marker capture test, demonstrating motion blur.

Rotational actuation for the Atlas full scale simulator relies on the normal forces exerted from the active mecanum wheels onto the sphere, which in turn incur large tangential roller forces which act on the surface of the sphere. While the Atlas TDP carries the same dynamic requirements, the full scale prototype requires forces that are orders of magnitude higher in order to fulfill the actuation requirements. This implies that the increase in actuation forces is a substantial increase in the tangential forces provided by the mecanum wheels, and considering the unbounded nature of the motions for which Atlas was designed, this means that the markers which provide orientation information undergo large shearing forces.

Overcoming these shearing forces and the resultant wear incurred on the VOS markers is of paramount importance for the longevity of the orientation control and actuation systems for Atlas. Material choices are inherently limited, as the material used to create the marker must be durable enough to avoid physical distortions caused by the shearing forces supplied by the active mecanum wheels, while simultaneously maintaining a low enough profile so as to not distort the spherical shape. Furthermore, the operation of the VOS requires that the markers be made of a material that possess a matte finish, enabling the accurate and consistent capture of the barcodes.

Through design iterations and adhesive testing, the material currently being employed for the markers on the full scale Atlas simulator utilizes polyvinyl chloride (PVC) markers; not only do these markers provide the matte finish required for the orientation function, it is a material that facilitates the application and removal of the markers onto a spherical surface without significant shape distortions. Initial durability tests indicate that the PVC markers will be more than capable of withstanding the tangential loading caused by actuating Atlas.

IV. Concluding Remarks

Over the past twelve years the Carleton University Simulator Project has moved from a small scale technological demonstration platform for proof of concept, to a full scale simulator prototype. Throughout the scaling process, many of the mechanical and actuation systems have undergone substantial redevelopment as a more robust understanding of the design and operation requirements has evolved.

Now within the final assembly and validation processes, the novel actuation architecture present within the Atlas motion platform has been well characterized. Necessary to this process was the development of testing procedures in order to finalize the design for the active mecanum wheels used to spin the sphere at its maximum intended angular rate of 35 degrees per second, at a rate of 225 degrees per second squared. Due to the interconnected nature of the orientation measurement and actuation systems, the scalability and material characteristics of the visual orientation system employed to control the absolute orientation of Atlas were also developed. During full scale operation, it is expected that the orientation of Atlas will be controlled to one tenth of a degree.

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