

Dynamic Symmetry for Orientation-Independent Planetary Mobility

Boxi Xia[†], Jiaxun Liu[†], Boyuan Chen

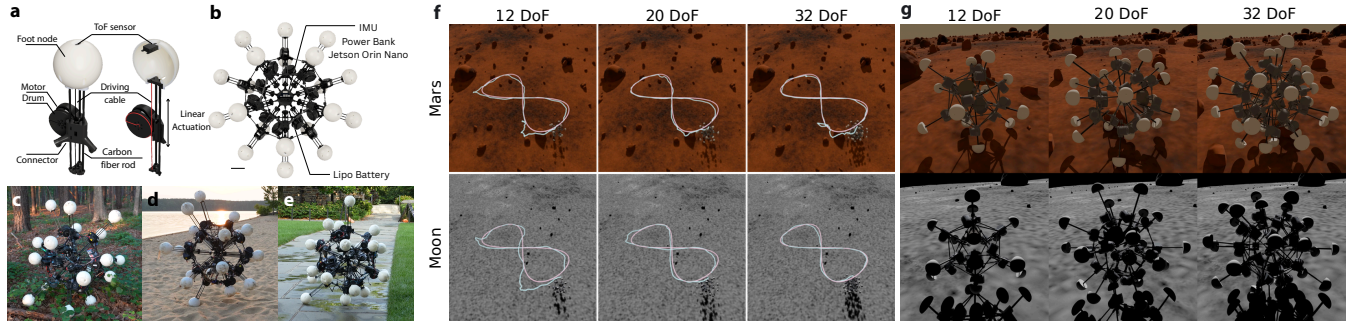


Fig. 1: **Argus platform, real-world locomotion and simulated planetary exploration.** (a) Argus leg module with a radially oriented 1-degree-of-freedom (DoF) cable-driven linear actuator and an time-of-flight (ToF) depth sensor. (b) The 20-leg dodecahedral Argus robot with near-extreme dynamic isotropy ($\eta = 0.91$). Scale bar, 0.1 m. (c–e) The flat-ground policy transfers zero-shot to unstructured outdoor terrain: dense foliage with high vegetation (c), soft sand (d), and grass and pavement (e). (f–g) Argus with 12/20/32 DoF following a figure-eight trajectory on simulated Mars and Moon terrain [1] with respective gravity. (f) Fixed top-down camera view with overlaid commanded (pink) path and actual (cyan) trajectory. (g) Camera view following the robot.

Abstract—Planetary ground robots can overturn while traversing crater slopes, uneven terrain, and obstacles. Most ground robots are designed around an upright body configuration and a forward-facing sensor view, making locomotion and perception sensitive to body orientation. Hopping and tumbling robots can tolerate large attitude changes, while other systems use dedicated mechanisms to recover a preferred orientation, but neither approach provides continuous locomotion across arbitrary body orientations. We developed Argus, a family of spherical robots with radially distributed actuators that enable locomotion across body orientations. We describe this property as dynamic symmetry and quantify it with dynamic isotropy, a measure of how uniformly a robot can accelerate its center of mass across directions. Across 1536 simulated morphologies, higher dynamic isotropy was associated with lower trajectory-tracking error, higher task success, and lower cost of transport. Argus’s distributed sensing further removes the need for a preferred viewing direction, supporting target tracking and perception-guided pushing. We further evaluated Argus under planetary conditions, demonstrating zero-shot trajectory tracking on simulated Mars and Moon terrains under reduced gravity. A physical 20-leg Argus with near-extreme dynamic isotropy climbed a parallel-wall under counterweight-emulated lunar gravity, continued locomotion with disabled actuators, and transferred zero-shot to cluttered and deformable terrain.

I. INTRODUCTION

Planetary ground robots must traverse rough, granular, and unmapped terrain in reduced gravity without servicing [2].

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Craters are common landforms on many planetary bodies and combine slopes, uneven terrain, and rocky obstacles. These features can disrupt ground contact and overturn a robot during traversal. Most conventional mobility systems are designed around an upright body configuration, with sensors oriented toward a forward viewing direction. Once overturned, the robot may lose effective contact with the ground or useful sensor coverage and must recover its nominal pose before resuming operation.

Some planetary robots tolerate large attitude changes by hopping or tumbling, while others actively recover a preferred pose. Hedgehog moves from whichever face is in contact with the surface using flywheel-driven hops and tumbles [3]. This mode is intended for microgravity small bodies rather than sustained locomotion under continuous surface loading. SpaceBok uses a reaction wheel to reorient during flight [4], while SpaceHopper uses its legs for attitude control [5]. Both ultimately return to a preferred configuration for surface locomotion.

Sustained locomotion on a loaded surface therefore remains tied to body orientation. We study a different actuation property, which we call dynamic symmetry. It is defined by the set of center-of-mass accelerations available to the robot and quantified by dynamic isotropy (Section II). A value near one indicates that the actuation geometry can generate near-uniform acceleration authority across directions. The same radial morphology also provides natural locations for distributed sensing. Each actuator can carry an outward-facing time-of-flight (ToF) camera, and the resulting depth measurements can be transformed into the world frame to maintain environmental observations as the body rotates.

We designed Argus [6], a family of spherical robots, to evaluate this relationship across 1536 simulated morphologies with fixed actuator redundancy. Our results revealed that higher dynamic isotropy was associated with better locomotion performance (Section IV). We also built a 20-leg Argus variant with high dynamic isotropy. The locomotion controller and perception of the physical system were both zero-shot transferred on wall climbing, locomotion after actuator loss, unstructured terrain, and perception-guided interaction (Section VII). Additional experiments using a space robotics benchmark [1] tested the same locomotion framework on simulated Mars and Moon terrain under reduced gravity through a zero-shot transfer.

II. DYNAMIC SYMMETRY AND DYNAMIC ISOTROPY

We define *dynamic symmetry* by how evenly a robot’s attainable center-of-mass (CoM) acceleration is distributed across directions. We note that this is different than morphological symmetry. Morphological symmetry concerns spatial orientation whereas dynamic symmetry concerns direction of action.

For a rigid-body legged robot, joint torques τ map to CoM accelerations $\mathbf{a}_c$ as

$$\mathbf{a}_c = \mathbf{A}(\mathbf{q}) \tau, \quad (1)$$

where $\mathbf{A}(\mathbf{q})$ is configuration-dependent and incorporates actuation directions, actuator limits, and mass distribution. For a unit direction $\mathbf{u} \in \mathbb{S}^2$, let $a_{\max}(\mathbf{u})$ be the maximum CoM acceleration attainable along $\mathbf{u}$ under actuator constraints. Sampling many directions on the sphere approximates the attainable acceleration set. *Dynamic isotropy* is then

$$\eta = \frac{a_{\min}}{a_{\max}}, \quad (2)$$

where $a_{\min}$ and $a_{\max}$ are the minimum and maximum values of $a_{\max}(\mathbf{u})$ across all sampled directions. As $\eta \rightarrow 1$, the robot accelerates almost equally well in every direction; when η is small, some directions are far harder to actuate than others.

We note that dynamic symmetry, measured by the above definition of dynamic isotropy, is a property of actuation capability. Geometric symmetry alone does not guarantee dynamic symmetry. For example, a conventional quadrotor has a highly symmetric airframe but low dynamic isotropy, because coplanar rotors cannot thrust laterally without first reorienting the body. Hence, it cannot generate instantaneous acceleration along the coplanar axis.

III. THE ARGUS ROBOTS

We present Argus, a family of spherical robots designed to explore the effects of increasing dynamic symmetry. Each Argus variant consists of 1-DoF linear legs mounted on a spherical frame and oriented radially toward the CoM. Because each leg applies force only along its own axis, the spatial distribution of leg directions shapes the attainable set. Adding legs increases actuation density, and distributing them more uniformly over the sphere raises η . We built a physical platform with 20 identical actuators at the vertices of

a dodecahedron with a dynamic isotropy $\eta = 0.91$ (Fig. 1a, b). It weighs 23.4 kg, spans 0.95 m fully retracted to 1.37 m fully extended, and carries its actuation, power, computation, and sensing entirely onboard. As η approaches one, actuation capability becomes nearly uniform in all directions. Without a preferred body orientation, the robot naturally will not suffer from overturning issues. When bumping into obstacles, Argus can continue to locomote with strong robustness.

IV. DYNAMIC SYMMETRY VERSUS PERFORMANCE

We tested whether higher dynamic isotropy correlates with performance across diverse tasks using the Argus variants. Because leg count changes redundancy, it is held fixed within each group to isolate the effect of isotropy. We generated Argus variants by varying both the number of legs and their placement on the sphere, and trained a locomotion policy by deep reinforcement learning for each morphology. We considered four tasks, evaluated at a commanded speed of 0.8 m/s: velocity tracking on flat ground, locomotion with 10% of legs disabled, payload transport between 0 and 20 kg, and traversal of discrete obstacles up to 0.1 m high. To separate isotropy from redundancy, we generated 512 morphologies at *each* of 12, 20, and 32 legs, for a total of 1536 robots, with leg directions sampled to span dynamic isotropy from 0.25 to 0.93 while the actuator count within each group was fixed.

Across all three leg counts and all four tasks (Fig. 2), higher dynamic isotropy consistently correlates with lower tracking error, higher success rates, and reduced cost of transport, and the fully symmetric designs lie at the high-isotropy end of these trends. Because redundancy is held constant within each group, actuator count cannot account for the trend. Redundancy still contributes where legs are disabled, since additional legs supply alternative contact configurations. Performance gains saturate as isotropy nears its limit. Our 20-leg Argus version lies in this plateau.

V. SIM-TO-REAL TRANSFER

Dynamic symmetry also simplifies system identification for sim-to-real transfer. Because all legs are mechanically identical and undergo relatively simple linear motions, identifying the dynamics of one leg or a set of legs on a single face of the robot allows the parameters of the remaining legs to be tuned simultaneously. For our 20-leg robot, we commanded the five ground-contacting legs to track excitation trajectories spanning a wide range of motion amplitudes and frequencies. We then tuned the proportional and derivative gains (k_p and k_d) in both simulation and the real system, as well as the armature, stiffness, and friction parameters in simulation, to minimize the discrepancy between simulated and real-world tracking errors. After identifying the physical parameters and determining appropriate domain-randomization ranges, all policies were trained in simulation and transferred zero-shot to the real complex and cluttered environment.

VI. PLANETARY LOCOMOTION SIM-TO-SIM TRANSFER

We trained the 12-, 20-, and 32-leg Argus variants on random obstacle and slope terrains under Earth gravity, and

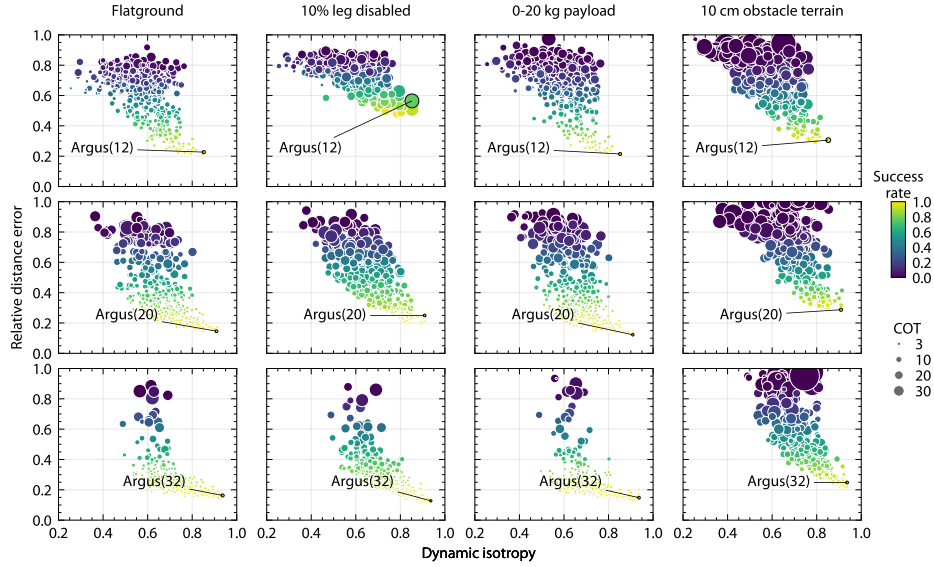


Fig. 2: **Effect of dynamic isotropy on performance across randomized Argus morphologies.** 512 morphological variants were evaluated at each of 12, 20, and 32 legs (1536 robots in total), spanning dynamic isotropy from 0.25 to 0.93. Each point corresponds to one morphology. The x axis denotes dynamic isotropy η and the y axes correspond to trajectory tracking error, task success rate, and cost of transport (COT) for all four tasks. Higher dynamic isotropy consistently correlates with lower tracking error, higher success rates, and reduced COT. Labeled “Argus” points are the fully symmetric designs, which lie at the high-isotropy end of the observed trends.

evaluated their trajectory tracking zero-shot on simulated Mars and Moon terrains at the corresponding reduced gravity, 3.72 m/s^2 and 1.62 m/s^2 . Fig. 1f, g show that all three variants tracked the commanded trajectory without retraining or gravity randomization. At a commanded 0.8 m/s , the 12-leg policy showed 0.603 m/s of velocity error on Mars and 0.505 m/s on the Moon; the 20-leg policy, 0.585 m/s and 0.474 m/s ; the 32-leg policy, 0.560 m/s and 0.488 m/s .

VII. HARDWARE RESULTS

We evaluated the performance of the 20-leg variant of the Argus robot with extensive real-world experiments.

A. Wall climbing under lunar gravity

In confined low gravity, both wheel traction and legged ground-reaction forces are limited. Between two rough parallel walls 1 m apart, Argus extended opposing legs against both surfaces and thrust upward with legs positioned diagonally to them. The policy selected bracing and thrusting legs from the wall geometry and its dynamics without the notion of a preferred robot attitude. In simulation under lunar gravity, Argus climbed at an average of 0.258 m/s with an 85.5% success rate, averaging 0.308 m/s across successful trials. On hardware, with lunar gravity emulated by a 19.5 kg counterweight on a pulley system [7], the robot climbed at an average of 0.238 m/s (Fig. 3d). During training, we randomly varied the gravity between 8.2% and 16.6% of Earth gravity. Argus climbed without gripping feet or attachment hardware, and training initialized the robot at random positions and orientations between the walls.

B. Resilience to actuator failure

Hardware deployed beyond Earth cannot be repaired easily, so a design with strong tolerance against damage such as actuator loss is essential. Due to the high dynamic symmetry and redundant design, Argus can reorient its body and bring healthy legs into contact to maintain the original task performance. The quantitative degradation curve was obtained in simulation. At 0.8 m/s , Argus retained 95% and 85% of its original velocity when two legs (10%) and four legs (20%) were disabled, respectively. Hardware experiments provided a coarser demonstration where the robot continued rolling forward with one to three disabled legs (Fig. 3c). When a disabled-leg configuration reduced propulsion efficiency, Argus reoriented its body to place functional legs in contact with the ground and continued moving.

C. Carrying Payload

Argus can also support payload transport. In simulation, Argus transported a 40 kg payload, nearly twice its body mass, while retaining 68.4% of its no-payload velocity at a commanded rolling speed of 0.8 m/s . In the hardware experiment, the payload was mounted asymmetrically on a single face of the carbon-fiber rod frame, whereas the payload was mounted in a balanced configuration in simulation. Argus carried 4.5 kg and reached 96.3% of the commanded 0.6 m/s rolling speed (Fig. 3a).

D. Unstructured and deformable terrain

Despite being trained only on flat terrain, the same policy transferred zero-shot to concrete bricks, grass, dense foliage, soft sand, and slippery wet surfaces (Fig. 1c–e). Discrete terrain was evaluated with a separately trained policy. On

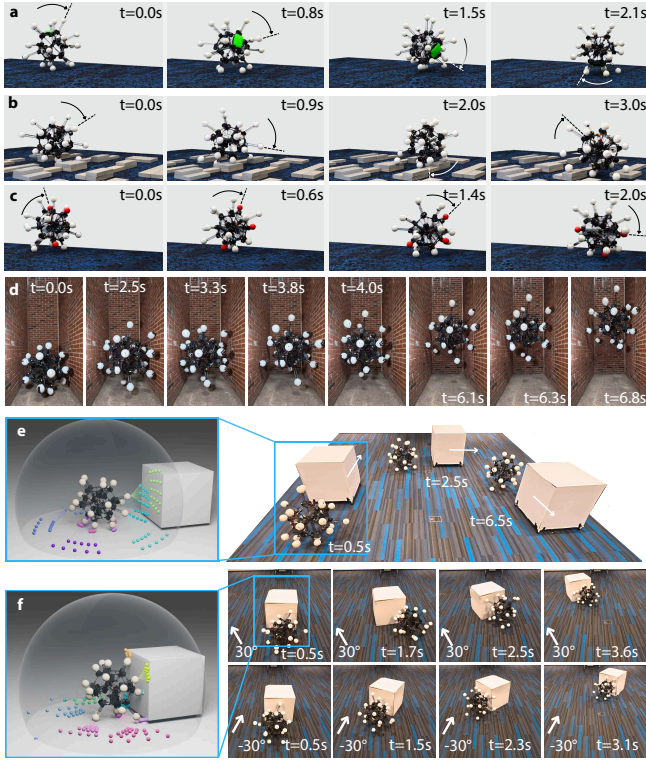


Fig. 3: Mobility and perception demonstrations with the 20-leg Argus. (a) Argus rolls with an asymmetrically mounted payload (green). (b) It reconfigures contact legs to traverse discrete terrain. (c) With one to three disabled legs (red), it reorients to bring healthy legs into ground contact. (d) Under counterweight-emulated lunar gravity, it climbs between parallel walls by alternating bracing and thrusting motions. (e) In simulation, fused depth measurements from 20 foot-mounted ToF cameras enable moving-target tracking. (f) In simulation, the estimated target state supports perception-guided whole-body pushing and following.

hardware, Argus succeeded in 15 of 18 trials (83.3%) over obstacles up to 0.12 m high while tracking a commanded speed of 0.6 m/s (Fig. 3b). The dense leg array allowed the robot to redistribute ground contacts across the body and maintain propulsion over the uneven surface. Our soft land experiments also provided promise for regolith deployment.

E. Onboard perception for autonomous interaction

Autonomous operation also requires sensing that remains usable after terrain-induced changes in body attitude, since a single forward-facing sensor can lose its view after the robot rolls. Argus therefore mounts a compact ToF depth camera at each of its 20-foot nodes. Transforming the depth measurements into the world frame produces a three-dimensional point cloud that is consistent across robot orientations. A point-cloud encoder estimates target state from these point clouds for use by the tracking and pushing controllers. Argus tracked a moving target with an 89.9% success rate in simulation and 36.8% on hardware (14 of 38 trials; Fig. 3e). For whole-body pushing and following, the success rate was

91.5% in simulation and 39.4% for the physical robot (13 of 33 trials; Fig. 3f). Repeated hardware experiments caused thermal degradation and loss of synchronization among the ToF modules, which accounted for most physical failures in both tasks.

VIII. CONCLUSION

Dynamic symmetry distributes actuation authority across the body and reduces dependency on any particular body attitude. We define dynamic symmetry and develop dynamic isotropy to quantify it. We further present Argus, a family of spherical robots to systematically study dynamic symmetry. In our results, dynamic isotropy was associated with lower tracking error, higher task success, and lower cost of transport across 1536 simulated designs at fixed actuator redundancy. After system identification and domain randomization, simulation-trained policies transferred zero-shot to the physical 20-leg Argus, which demonstrated wall climbing under emulated lunar gravity, actuator-loss resilience, unstructured-terrain traversal, and orientation-independent perception. Simulated Mars and Moon experiments further demonstrated zero-shot transfer under reduced gravity.

Our experiments remain an initial terrestrial evaluation of the design. Counterweight offloading reproduces the gravitational load only approximately and does not reproduce reduced-gravity contact dynamics. Soft sand similarly captures only some mechanical aspects of planetary regolith. The current ToF array also developed synchronization failures during repeated operation because of thermal degradation, highlighting important challenges for sim-to-real transfer. Longer-duration operation will require improved thermal management and synchronization. The cable-driven actuation system has not yet been tested under vacuum, thermal cycling, radiation, or sustained dust exposure, all of which would need to be addressed before planetary deployment in our future studies.

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