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# DESIGN OF A PASSIVELY-ADAPTIVE THREE DEGREE-OF-FREEDOM MULTI-LEGGED ROBOT WITH UNDERACTUATED LEGS

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## ABSTRACT
*This paper discusses the design of a three degree-of-freedom (3-DOF) non-redundant walking robot with decoupled stance and propulsion locomotion phases that is exactly constrained in stance and utilizes adaptive underactuation to robustly traverse terrain of varying ground height. Legged robots with a large number of actuated degrees of freedom can actively adapt to rough terrain but often end up being kinematically over-constrained in stance, requiring complex redundant control schemes for effective locomotion. Those with fewer actuators generally use passive compliance to enhance their dynamic behavior at the cost of postural control and reliable ground clearance, and often inextricably link control of the propulsion of the robot with control of its posture. In this paper we show that the use of adaptive underactuation techniques with constraint-based design synthesis tools allows for lighter and simpler lower mobility legged robots that can adapt to the terrain below them during the swing phase yet remain stable during stance and that the decoupling of stance and propulsion can greatly simplify their control. Simulation results of the swing phase behavior of the proposed 3-DOF decoupled adaptive legged robot as well as proof-of-concept experiments with a prototype of its corresponding stance platform are presented and validate the suggested design framework.*

## INTRODUCTION
When dealing with the problems of robotic locomotion, legged robots can offer significant advantages over wheeled robots when dealing with rough terrain, including obstacles present in human environments. By utilizing discrete contact points with the ground and the ability to lift their legs over obstacles and other discontinuities in the terrain, legged robots generate stance configurations that are used to propel the body forward and stabilize it while walking. Many multi-legged *walking* robots, e.g. those relying on statically-stable gaits to remain upright, have been designed with legs of high kinematic complexity that have a large number of actuators to allow for complete control over the motion of the feet relative to the body (e.g.[1]). However, such designs tend to suffer from actuator redundancy in the stance phase, with more control inputs required than independently controllable degrees of freedom in the stance platform. Indeed, any legged robot with greater than six actuators engaged during stance is necessarily redundant, and this limit can be lower depending on the specific design in question. Moreover, in the absence of additional internal freedoms, such robots are also kinematically over-constrained in stance, potentially leading to destabilizing forces acting on the robot or the violation of the contact constraints.

While over-constraint is not necessarily a problem, it does make effective control of a robot difficult due to the over-determined nature of the system. Some control techniques developed to deal with this issue include the avoidance of over-constrained motions [2] and impendence control [3]. While these and other control laws have been shown to work under specific conditions, they generally rely on either low-impendence actuators or high-fidelity output sensing, both of which are difficult to accomplish in practice. Additionally, the presence of redundant actuators in stance lead to heavier and

 

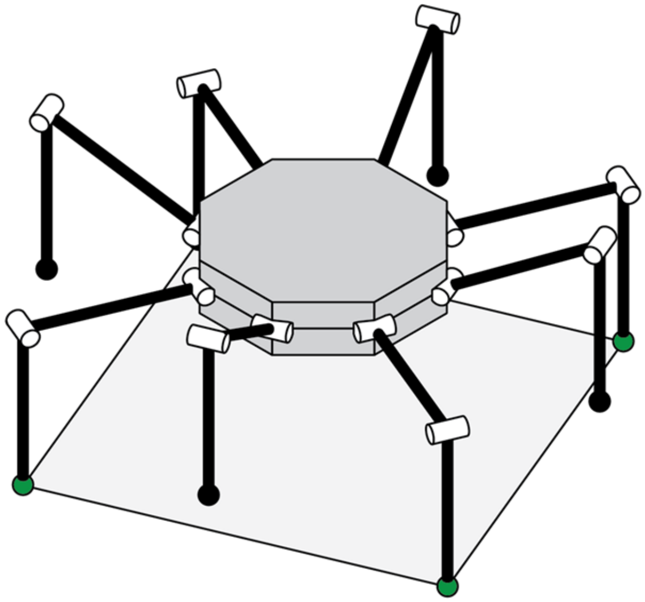

Figure 1. DIAGRAM OF THE 3-DOF NON-REDUNDANT ROBOT DESIGN WITH ITS SUPPORT PATTERN.

more power-hungry robots, both undesirable characteristics for untethered mobile operation, while the passive compliant mechanical elements that have been used to mitigate over-constraint introduce more points of failure into the system.

Legged locomotion can broadly be classified into one of two gait types – those that are statically-stable and those that are dynamically stable, often modeled after systems such as the Spring-Loaded Inverse Pendulum [4]. Robots designed to exploit their natural dynamics are often capable of fairly quick locomotion, but often at the cost of control over ground clearance and body posture. Kinetostatic walking robots, on the other hand, generally sacrifice locomotion speed for more robust ground clearance and greater stiffness in stance. The earliest multi-legged robots, such as the Adaptive Suspension Vehicle [5] and PVII [6] implemented statically stable gaits to prevent the robot from falling over at the expense of gait speed. With robots such as RHex [7], SCOUT II [8], and Sprawlita [9], passive compliant joints were added to allow for faster dynamic gaits. More recently, robots such as BigDog [10] and StarlETH [11] have demonstrated impressive dynamic locomotion performance through complex closed-loop feedback control with a large number of sensory inputs.

In previous work [12], we presented the design of a full-mobility non-redundant legged robot illustrating the use of exact-constraint as a design tool for the stance behavior of legged robots. We then outlined a general framework for the design of non-redundant walking robots using the principles of exact-constraint and under-actuated mechanisms, with initial applications for full-mobility robots [13]. In this work we extend that framework through the decoupling of stance and locomotion to design a lower-mobility robot with only three actuators active in stance (Fig. 1). The proposed legged robot utilizes a single actuator per stance platform to raise and lower the legs in swing and its body during stance, and utilizes a simple 2-DOF planar mechanism for locomotion, moving the two frames relative to one another.

This paper is organized as follows. We begin with a brief overview of the principles behind the design of non-redundant walking robots and a review of the goals for this design. This is followed by a description of the specific design of the 3-DOF legged robot and its nominal behavior during both the stance and swing phases of locomotion. We then present the results of a simulation of the swing phase behavior of the proposed adaptive non-redundant legged robot and the experimental validation of its stance platform design. We finally summarize the main results and discuss future work.

## NOMENCLATURE

| | |
|---|---|
| $T$ | Tendon tension |
| $r_i$ | Joint pulley radius |
| $\theta_i$ | Joint angle |
| $\ell$ | Coupling constraint value |
| $L_{dist}$ | Distal link length |

## DESIGN METHODOLOGY

In this section, we describe the principles behind the design of non-redundant walking robots through the use of kinematic mobility and underactuated mechanism design tools. The goals for this specific design are listed followed by a description of decoupling different body DOFs.

### Non-Redundant Kinetostatic Robot Design

The main principle driving this design method is the use of the smallest number of actuators or control inputs to realize a desired locomotion goal. When designing a legged robot with fewer than 6 DOF, the task may be approached in one of at least two ways – one option is to synthesize a stance platform with the requisite DOFs and then actuate the required number of joints. Alternatively, a full-mobility platform may be synthesized after which actuator reduction tools are used to reduce the number of DOFs in the platform. In this work, we use the latter approach.

The kinematic analysis of a legged robot in stance is dependent on a number of assumptions. Perhaps the most crucial is the assumed behavior of ground contact – this has implications in the synthesis of potential leg designs as well as the resulting body DOF from control of different joints in the system. We use a point contact with friction assumption [14], a contact model that is kinematically equivalent to a spherical rotation about the contact point. For simplicity we also limit our legs to serial chains of either revolute or prismatic joints. If we use the Chebyshev-Grübler-Kutzbach (CGK) criterion [15,16] as a lower-bound on the kinematic mobility of a given stance platform, we see that any leg permitting 6-DOF motion between the foot and body can be used to generate a platform with full mobility. The specific kinematic structure of these legs

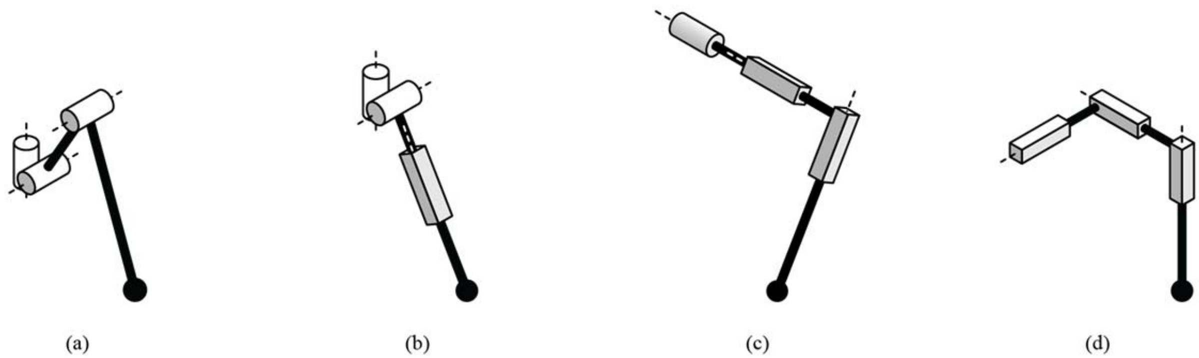

Figure 2. SELECTION OF 3-DOF SERIAL KINEMATIC CHAINS THAT CAN SERVE AS LEGS FOR WALKING ROBOTS WITH JOINT AXES INDICATED; THE KINEMATIC PAIRS USED ARE [R]EVOLUTE AND [P]RISMATC: (a) RRR, (b) RRP, (c) RPP, AND (d) PPP.

is dependent on the assumed behavior of ground contact; given the spherical joint assumption described above, any leg design with three non-redundant single-DOF joints should allow for full platform mobility in stance, with any number of legs. A selection of potential leg topologies is presented in Fig. 2.

In order to reduce the unconstrained mobility of a stance platform we must passively constrain its joints. The most basic form of constraint is simply locking / removing a joint; it generally reduces the mobility of the platform by one although this may not be the case in singular or ill-conditioned configurations [17]. Additionally, joints can be rigidly coupled together using gears or linkages to reduce the mobility of the platform. More interestingly, adaptive constraints such as tendon couplings or linkages, traditionally used in underactuated mechanisms [18], apply constraints in the form of linear relationships between joint values, resulting in different platform motion and reducing the dimensionality of the workspace of the mechanism. Note that different combinations of constraints will result in different available body degrees of freedom.

Once a stance platform with the desired degrees of freedom has been synthesized, the final task is to allocate actuator effort in such a way as to achieve locomotion tasks while also making sure not to use more actuators than controllable degrees of freedom in stance. This can be accomplished through a combination of directly-driven joints as well as rigidly- and adaptively-coupled joints. In this way we can be sure that our robot will be exactly-constrained in stance. While this will almost certainly result in uncontrollable leg degrees of freedom in the absence of contact, the judicious use of springs and other elastic elements can ensure that the swing trajectory of the leg tends towards stable stance configurations. Elastic elements, by shaping the energetic state of the robot, lead to different nominal robot behaviors, but do not actually impose kinematic constraints on the system as the joints they affect are still free to move, albeit at a higher energy cost than before.

This methodology generates robots that are exactly-constrained in stance, thereby capable of withstanding disturbances while in contact with the ground. These robots also only control a specific set of desired body degrees of freedom, leaving the rest constrained, with the minimal number of actuators necessary to do so, preventing the need for redundant control and resulting in lighter and simpler robots.

### Decoupling Stance and Locomotion

The vast majority of legged robots consist simply of a body connected to the ground by a set of legs. In this case, the robot in stance constitutes a parallel mechanism whose task it is to move the body relative to its points of contact with the ground. In contrast to parallel robots, where joints are physically attached to the fixed and moving platforms, legged robots must be capable of achieving the desired motion regardless of variations in the contact points themselves. Additionally, determining the actual robot configuration in each stance phase would require the addition of an array of sensors and the use of closed-loop feedback control.

Beyond the uncertainty of the robot's configuration, parallel platforms have, in general, a fairly small workspace; in the context of a legged robot the size of the workspace in its stance phase is directly linked to its stride length, which is in turn directly related to its walking speed. These limitations, among others, have led researchers to focus on exploiting the dynamic behavior of mobile robots to increase the speed of locomotion, effectively abandoning statically-stable walking robots.

An additional challenge in the control of legged robots is the inherent coupling between stance and locomotion. As mentioned previously, mapping the actuator space of a traditional parallel platform to the task space or to specific body DOF's makes control over specific DOF's difficult to achieve in isolation. To that end, we propose decoupling the stance and locomotion mechanisms of our robot, sidestepping this issue entirely. This provides a number of performance benefits in addition to the simplicity of control. Since the locomotion

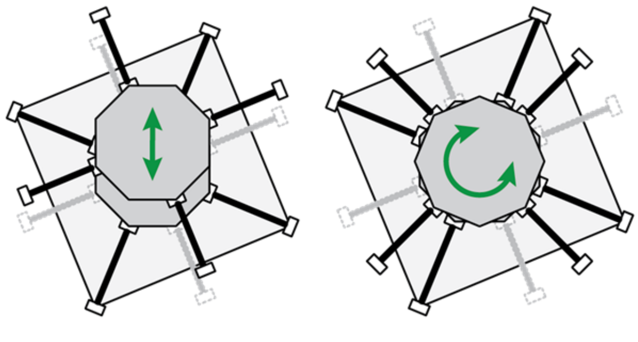


Figure 3. DIAGRAM OF ROBOT'S LOCOMOTION MECHANISM; (a) PROPULSION AND (b) STEERING.

mechanism is purely designed to move the body relative to the feet, its workspace in those degrees of freedom can be much larger than in a similarly sized parallel mechanism. As long as we can ensure that the robot remains stable, e.g. we do not bring the center of mass too close to the edge of the robot's support pattern, we can increase the stride length of our robot dramatically. Additionally, we have the ability to shape the workspace of the locomotion mechanism depending on the desired task (e.g. primarily forward motion vs. the ability to make tight turns).

These benefits do not come without some tradeoffs – the separate locomotion mechanisms are often less compact and heavier than simple parallel designs. Moreover, this concept is not entirely novel to legged robots. MELWALK III [19] was designed with two three-legged platforms with 1-DOF legs and a straight-line mechanism for propulsion. DANTE II [20], designed to explore volcanos, utilized two four-legged frames with 1-DOF pantograph legs. Finally, the ParaWalker II robot [21] consisted of two fixed three-legged frames connected by a 6-DOF actuator. While the first two followed the principles outlined above, they both suffered from over-constraint in stance and actuation redundancy. Moreover, DANTE II had a severely limited locomotion workspace, particularly steering with maximum turns per step of $\pm 7.5°$. We expect that by combining this decoupling with under-actuation in swing, robust passive terrain adaptability during walking can be efficiently achieved.

## ROBOT DESIGN

In this section, we describe the synthesis of a robot design following the methodology described above. First, the specific goals for the design are presented. The locomotion mechanism is broadly described along with a non-redundant 1-DOF stance platform. The swing phase behavior of the robot is investigated as well leading to the selection of a leg coupling scheme.

### Design Goals

The primary motivation for the design of the proposed legged robot was to simplify its control and mechanical design while still maintaining the ability to achieve effective locomotion over uneven terrain and robustness in stance, that is, the robot is capable of resisting disturbance forces and supporting its own weight and any payload. We also desired that some nominal clearance is maintained between the body of the robot and the ground since one of the advantages of legged locomotion over wheeled locomotion is the ability to restrict ground contact to a set of discrete points and thereby isolate the body from the ground. Finally, but not least significantly, legged robots are intended to be mobile; it was therefore important that the robot be capable of achieving nominally planar motion by moving its contact points relative to its center of mass (or vice versa) .

With these goals in mind, a minimal subset of required controllable body degrees of freedom were selected. In order to effect locomotion, we chose propulsion, or forward motion, designated as translation of the body in the $x$ direction. In order to provide the second DOF for planar motion we chose steering in the form of yaw, or rotation about the $z$ (vertical) axis. Finally, since at a minimum a legged robot needs to stand and exert weight-supporting loads, the final body DOF selected was translation in the $z$ direction. While the remaining body DOFs (roll, pitch, and lateral translation) could be used to either precisely control the robot's posture and/or achieve roughly holonomic planar motion, the selected three degrees of freedom are sufficient for the development of an effective mobile robot.

### Locomotion Mechanism

As mentioned previously, the decoupling of stance and locomotion in a legged robot could result in much simpler control and better walking performance, particularly when combined with a non-redundant, exactly-constrained stance platform. In this robot, we decided to utilize the legs of the robot purely to for weight support and the control of ground clearance. This would be achieved through the use of two identical stance platforms connected by a 2-DOF planar mechanism (for example, a linear actuator and servomotor in series) that both rotates the platforms relative to one another as well as translates them in a single direction. The most basic gait of the robot would involve the movement of the non-contact platform as close to the stable bounds of the stance platform as possible, lowering its legs and transferring the weight of the robot onto them, then bringing the old stance platform forward to the next contact point. These DOFs illustrated in Fig. 3.

One drawback of this design is its turning behavior. While the rotation of the platforms about their centers could provide an almost non-existent turning radius, the fact that the locomotion mechanism is a serial combination of the two (e.g. the rotation mechanism is only fixed relative to one of the platforms) means that the motion of the swing feet in a direction other than forward can only happen when the steering platform is in stance. When the propulsion platform is in stance the steering platform can rotate in preparation for the next step, but the platform itself will only move in the direction the propulsion platform is oriented in.

Another consideration, but not necessarily a drawback, of this design is the fact that the locomotion behavior of the robot will be non-holonomic (assuming an effectively planar locomotion space). That said, due to the decoupling of stance and locomotion we could easily switch this 2-DOF mechanism with a 3-DOF mechanism that includes lateral motion for more flexibility, should our use case require it.

## Stance Platform

Now that all the locomotion mobility has been delegated to a separate mechanism, the legs of the robot have only a single responsibility – supporting the robot and ensuring some nominal height above the ground. To this end, we desire a 1-DOF platform whose nominal controllable motion is towards or away from the ground. Following the methodology outlined previously, we first define a full-mobility platform topology that we can then reduce. This includes both the determination of the required number of legs as well as their kinematic structure. For this robot we will utilize four legs per platform for greater symmetry and a larger support pattern in stance, increasing our effective stride length. For the initial full-mobility platform, we select the RRR kinematic leg topology (Fig. 2a), a versatile and common leg topology also known as the Universal-Revolute-Spherical leg [22]. One advantage of this leg design is that it inherently decouples “out-of-plane” motion of the leg, as controlled by the hip abduction joint, and the “in-plane” motion of the leg, or its length and flexion, as controlled by the hip and knee flexion joints.

We then reduce the platform mobility to 1-DOF of actuation through the removal of joints and application of constraints; in this case, we have to remove a total of 5 passive degrees of freedom. The first four are straightforward – we remove the hip abduction joint of each of the four legs. Since the motion of all the legs lies in planes which share the $z$-axis, the platform retains translation in the $z$ direction as permissible motion. The total free mobility of the platform is now 2, including a coupled pitch/roll DOF. Another way to think of this is as if we had actuated each of those joints instead – from a constrain perspective it is equivalent. We still need to remove an additional degree of freedom; however, this will be influenced by the way we actuate our legs.

## Stance Actuation

One of the biggest challenges in designing non-redundant robots, particularly those with lower mobility, is ensuring that the actuator effort is distributed between all of the legs. Particularly in our case, where we only have a single actuator, we need to ensure that we have the means to effect some control over each of the legs. Fortunately, the field of underactuated mechanisms has spent decades designing systems to do precisely that – control multiple degrees of freedom with fewer actuators. These systems have been particularly effective in the design of manipulators, providing

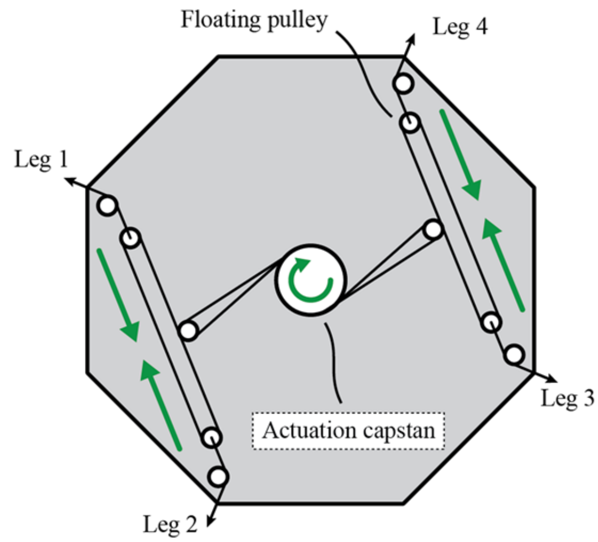


Figure 4. DIAGRAM OF ADAPTIVE BETWEEN-LEG COUPLING USED TO ACTUATE THE PLATFORM.

robustness and flexibility without the power requirements and complexity of fully-actuated designs [23,24].

Continuing the design of our specific platform, we have a total of 8 joints between all of the legs, with the limit of two constraints between all of them. If this were simply a parallel platform, we could actuate any combination of two joints and control the platform; however, since we also need to move all of the legs during swing, we must be able to move each one of them. Another way to conceptualize of these constraints is as additional information for the system of equations needed to solve for the platform’s configuration. Therefore, any independent combination of the platforms joints should work.

The design tool we chose for actuation is the adaptive tendon coupling (Fig. 4), which has been used with great success in manipulation [18,23]. Such couplings allow for the distribution of force across multiple joints and define an inequality constraint on the positions of those joints of the form:

$$\sum_{i=1}^{j} \alpha_i r_i \Delta\theta_i \geq \Delta\ell \qquad (1)$$

where $\alpha_i$ is the sign of the coupling at joint $i$ (positive or negative), $r_i$ is the effective pulley radius the tendon goes around at that joint, $\Delta\theta_i$ is the change in joint angle at that joint, and $\Delta\ell$ is the overall change in tendon length. The reason why this is an inequality is because tendons can only pull, not push, so it is possible for external forces to move the system in such a way that the tendon goes slack.

Regardless, each linearly independent adaptive coupling exerts a single constraint on a mechanism when engaged. From a behavioral perspective, adaptive couplings by themselves only define the relationship between different joints but not

 

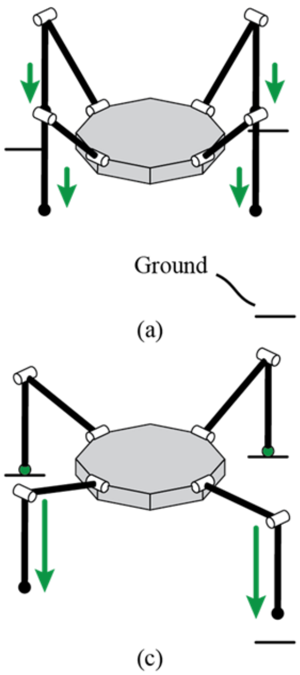


Figure 5. DIAGRAM OF ADAPTIVE SWING PHASE BEHAVIOR (a-d). THE LENGTH OF THE ARROWS INDICATES THE MAGNITUDE OF RELATIVE MOTION.

their actual values. However, in the context of the entire stance platform they provide the necessary constraints, along with the kinematic structure of the platform, to be exactly-constrained when all four feet are in contact with the ground. Based on this, we chose to adaptively couple the hip joints between each of the two pairs of legs on the platform, leaving the knee joints entirely passive. This has implications on the swing behavior of the platform that will be addressed in the next section. Moreover, the choice of which specific legs to couple together is also highly dependent on the desired spring behavior. Regardless, this still does not conclude the design of the stance platform; the two couplings would each need an actuator to define the tendon length, leaving each platform with two actuators.

In order to reduce our platform to a single actuator, we decided to rigidly couple the two tendon constraints together (see the central capstan in Fig. 4). In other words, $\Delta\ell_1 = \Delta\ell_2$, providing the final constraint necessary to reduce our stance platform to a 1-DOF mechanism. With the actuator fixed, the system is exactly-constrained, while any motion of the actuator would be distributed to all four legs through the tendon couplings, resulting in motion of the body away from the ground. Now that we have achieved the desired stance behavior, we need to ensure that the swing behavior of the leg will lead to stable contact with the ground.

## Swing Behavior

The use of adaptive underactuation between legs has exciting implications for how the swing legs make contact with the ground. As we mentioned previously, the tendon constraints only determine the relationship between the coupled joints but not their actual positions. This means that the system remains under-constrained even after one of the feet hits the ground and can no longer move. As such, the other leg continues to move until it, too, makes contact with the ground (Fig. 5). Since the tendon tension remains fairly low while the actuator is moving – entirely based on the stiffness of the springs opposing the leg motion – ground contacts do not exert high forces on the robot, preventing it from being destabilized. This adaptive behavior allows the robot to make contact on terrain with significant variability without any sensing, a significant advantage.

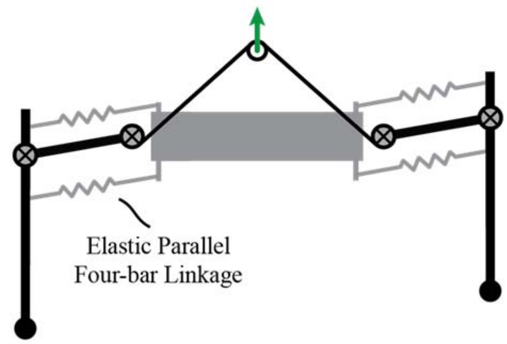


Figure 6. COUPLED LEGS WITH ELASTIC PARALLEL FOUR-BAR LINKAGE TO KEEP DISTAL LINK NOMINALLY ALIGNED WITH THE BODY Z-AXIS.

Until this point, we have neglected the behavior of the passive knee joints; now that the platform is no longer exactly-constrained, all of those joints are entirely free to move. In the absence of any further modifications to the system, this would likely mean that they would always point in the direction of gravity, attempting to reach a minimal-energy configuration. This, however, may not be quite what we want. Since the knee joint is passive, any equilibrium reaction forces must pass through that joint to avoid a net moment. With this in mind, we can ensure that the ground contact forces are nominally aligned with the $z$-axis of the body using an elastic parallel four-bar linkage (Fig. 6), increasing the likelihood of those forces being within the friction cone at the foot. For a full discussion of this design please see [12].

All that remains is to determine which of the legs we will couple together. This is important because of the rigid coupling between the two pairs; since we ensure that the two tendons are the same length, once one pair is in full contact (e.g. both feet are on the ground), then the tendon length is fixed and the actuator will stall. If only one or neither of the legs of the other pair have made contact with the ground, then the robot will not be stable on the ground and as soon as the prior stance frame transfers the weight over to the new frame, the robot will reconfigure until it either makes contact with all four feet on the ground or falls over. We want to ensure that this weight-acceptance motion of the robot will lead to stable stance.

Looking at our stance platform, we basically have two options when it comes to leg coupling due to symmetry – we can either couple opposite legs together or couple adjacent legs

 

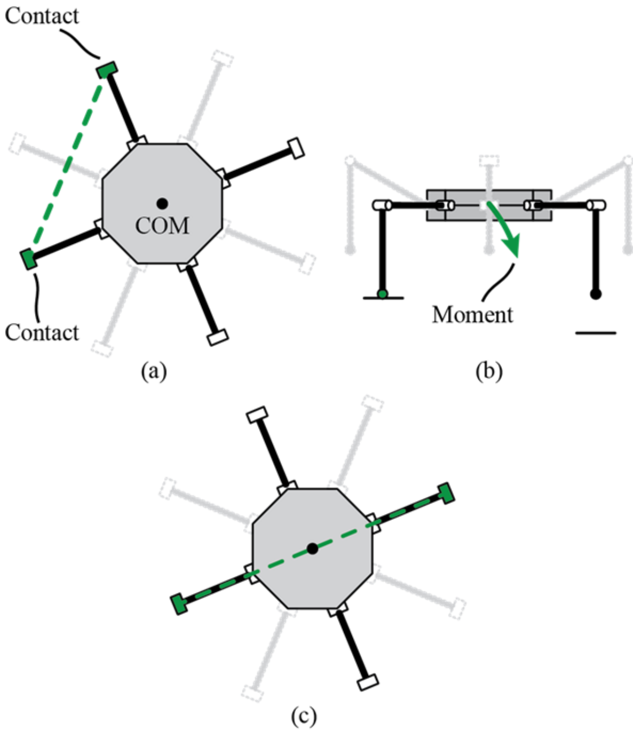


Figure 7. LEG COUPLING OPTIONS; (a) ADJACENT LEG COUPLING LEADS TO STABILIZING MOTION OF BODY (b), WHILE OPPOSITE COUPLING (c) MAKES STABLE CONTACT UNLIKELY.

together. While this choice may seem arbitrary, it actually has a significant impact on the likelihood of achieving full contact. Fig. 7 shows an illustration of the two potential pairings. In either the two-contact or three-contact case, the robot is highly under-constrained and will not be stable until either all four feet are on the ground or the body of the robot hits the ground. Due to the active tendon constraint on the contacting pair, we can expect those legs to be much stiffer than the free legs and therefore that the robot will rotate about the axis defined by the two contact points. If we couple opposite legs, as in Fig. 7c, the robot's center of mass will generate a net moment towards one direction or the other. The problem is that motion of the body so that one free foot approaches the ground *necessarily* results in the other free foot moving away from the ground, making full contact almost impossible. On the other hand, if we couple adjacent legs together as in Fig. 7a, we see that the moment generated by the center of mass about the contact axis will generate motion bringing *both* of the free legs towards the ground, thereby stabilizing the robot.

To summarize, the expected swing phase behavior of the robot is as follows: the legs of the robot are brought to the ground by the actuator, with the adaptive coupling ensuring a minimum of two feet in contact before any significant contact forces are generated. Once the tendon constraint is active on either pair, the robot will rotate about the axis generated by the

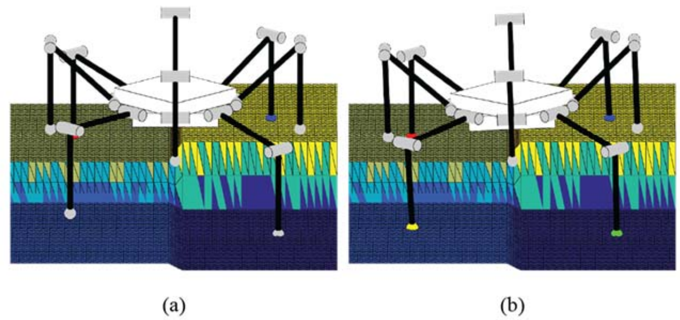


Figure 8. SIMULATED CONTACT CONFIGURATION (a) WHEN ACTUATOR LOCKS AND (b) POST-RECONFIGURATION.

two feet in contact with the ground until full contact, and therefore stabile stance, has been achieved.

### Summary

In this section we presented the specific robot design generated using the methodology presented above. The robot has eight RR legs distributed between two identical platforms that are connected with a 2-DOF planar mechanism. The hip joints of adjacent legs are adaptively coupled together with the two pairs of each platform being rigidly coupled together to give a 1-DOF platform in stance. The use of elastic elements allows for the nominal behavior of the passive knee joint to be set, and the adaptive coupling allows the robot to passively find stable contact on uneven terrain.

## SWING PHASE SIMULATION

In order to verify the swing phase benefits of using adaptive couplings and the viability of the design, a basic simulation was designed for a single platform. The goal was to analyze the expected contact locations and final stance configuration of a robot after the swing phase. A complete kinematic representation of the robot was described including all constraints, adaptive and rigid, and an approximate expression for the total system energy as a function of configuration was compiled including return springs and the elastic linkage as described in the previous section. None of the joint angles were directly controlled – all inputs to the system were through the coupling tendons as described above.

For each trial, the body of the robot was fixed in space to represent the initial stance platform being exactly-constrained with the *z* height of the center of mass being equal to the distal link length. The ground height beneath each of the four swing feet was varied independently between positive and negative of one third the distal link length to simulate differently oriented rough terrain. This included some redundancy due to the symmetry of the system but we felt that it would eliminate out any directional influence on the results.

Once the initial configuration was set up, the tendon constraint values necessary to make contact for each feet were determined. The order of contact was determined by increasing the tendon length until two coupled legs had both made contact with the ground. At that point, the motion of the robot body during weight transfer was assumed to be a pure rotation about the axis connecting the two coupled contact feet, and this was performed until all four feet were in contact with the ground. After full contact the feet were locked in place and the body was released to find the new stance configuration of the robot. The final robot configuration was then stored. The simulation also noted if it failed to find a solution. Fig. 8a shows an example of the configuration of the robot when the actuator locked and Fig. 8b shows the final configuration.

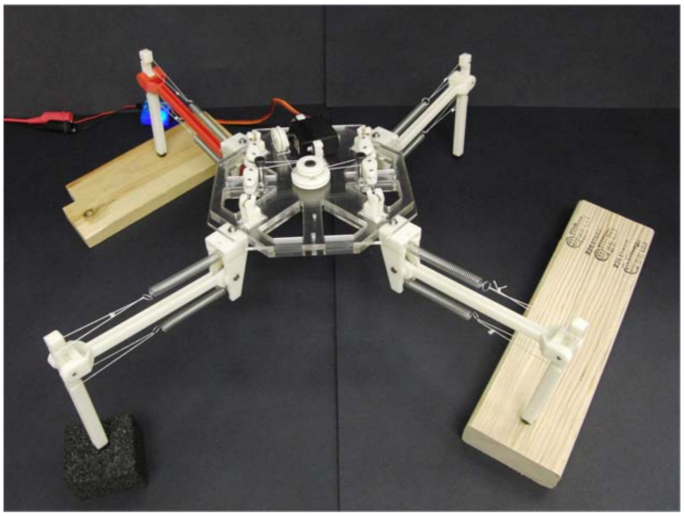

Figure 9. PHOTOGRAPH OF PROTOTYPE STANCE PLATFORM STANDING ON SIMULATED TERRAIN.

The ground height range was discretized into seven steps for a total of 2401 possible ground height combinations, and the solver converged for 2096 (87%) of them. The average deviations of the final position (normalized by distal link length) and posture of the body from the prior stance location is shown in Table I.

If we consider the actual terrain variability allowed based on the robot parameters, the actual inclination of the terrain was permitted to vary between $\pm 15.6°$. Assuming that the robot merely conformed to the inclination of the ground beneath it, we would expect the average roll and pitch to be roughly 7.9°. As we can see, the adaptive swing behavior allowed the robot to be much closer to contact before “falling” into its final configuration, resulting in lower postural changes. Another thing to note is the difference between roll and pitch; since the $y$ axis was basically normal to the contact axis, we would expect the robot to roll more than pitch during the final reconfiguration. Finally, while the large vertical deviation might be disconcerting, it is important to note that the simulation did not actually take actuator effort into account. In practice we would expect the additional force exerted by the actuator in stance lift the body up and bring it closer to the initial height above ground.

Table 1. AVERAGE POSTURE AND POSITION DEVIATION POST-CONTACT IN SIMULATION

| Parameter | Value |
|---|---|
| Roll ($\boldsymbol{\theta_x}$) | 5.4° |
| Pitch ($\boldsymbol{\theta_y}$) | 4.5° |
| Yaw ($\boldsymbol{\theta_z}$) | 1.3° |
| Forward Motion ($\boldsymbol{x}$) | $0.044 \cdot L_{dist}$ |
| Lateral Motion ($\boldsymbol{y}$) | $0.062 \cdot L_{dist}$ |
| Vertical Motion ($\boldsymbol{z}$) | $0.118 \cdot L_{dist}$ |

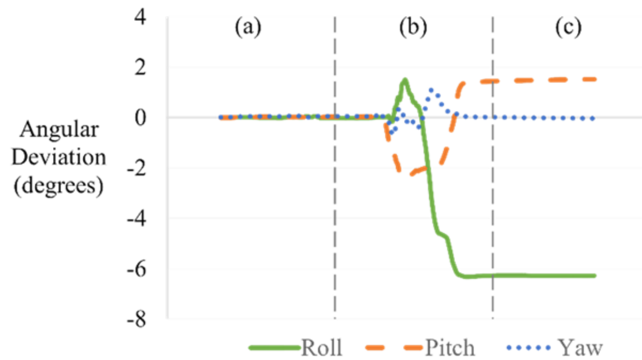


Figure 10. PLATFORM POSTURE DEVIATION FROM A SINGLE TRIAL; (a) PRE-COUPLED CONTACT, (b) CONTROLLED FALL, AND (c) FINAL POSTURE

## PROTOTYPE EVALUATION

In order to validate the design approach, a prototype stance platform was built (Fig. 9). As a reminder, a complete robot would consist of two such platforms connected by a 2-DOF locomotion mechanism. The legs and coupling components were constructed using 3D-printed parts (Stratasys ABS*plus*) and the platform base was laser-cut out of acrylic. The hip radius (distance from center of robot to hip joint) was 105 mm and the proximal and distal link lengths were 150 mm. The foot of the robot terminated in a rubber hemisphere to improve frictional contact with the ground and prevent slipping to satisfy our contact assumptions. The platform was actuated using a Power HD 1501MG servo motor.

The platform was placed on a rigid frame with objects of varying heights placed beneath each foot. The motor was driven until coupled contact was made, then the support was carefully removed, allowing the platform to reconfigure naturally. The posture of the platform was recorded using a VectorNav VN-200 Rugged inertial measurement unit connected to an Arduino microcontroller. Fig. 10 shows the data from a single trial, lasting about 30 seconds. The platform was able to stand stably on all combinations of ground height and was robust against disturbance loads (e.g. if it was pushed), even in cases where the feet slipped during weight transfer. In all recorded trials the change in pitch was less than 7° and the change in roll was less than 2°, with negligible yaw. These results are encouraging for the use of this platform as part of a complete legged robot, which is being completed and will be tested in future work.

## CONCLUSION

In this paper we presented the design of a non-redundant 3-DOF adaptive walking robot with decoupled control over its height above ground and locomotion (propulsion and steering). This design was synthesized through the combination of kinematic mobility analysis and techniques of under-actuated mechanisms, resulting in a legged robot that passively adapts to variations in the terrain height beneath it while remaining stable and exactly-constrained in stance. A simulation of the swing / weight-transfer phase behavior of the robot was conducted, showing that this design would result in a more consistent body posture across uneven terrain. A prototype stance platform was constructed and the simulation results were verified, thus validating the suggested design framework.

Looking forward, we plan on constructing a full robot prototype, including the locomotion mechanism, and conducting locomotion trials across a variety of terrains. These will include smooth flat terrain, rough flat terrain, smooth inclined terrain, and rough inclined terrain. We expect to demonstrate robust locomotion regardless of terrain type. We would also like to determine the effect of the leg compliance on the stability of the robot and its control, as well as optimize the springs' stiffness to minimize the required actuator effort during locomotion. Additionally, we plan to investigate the performance benefits, if any, gained by increasing the number of controllable body DOF, both by increasing the platform mobility and by utilizing more complex between-frame mechanisms.

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