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Artificial Restraint Systems for Walking and Running Robots: An Overview

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Many efforts to develop walking and running robots utilize a boom or other device to catch the robot when it falls, sense the position of the robot, and constrain the robot to operate in a two dimensional plane. However, publications usually focus on the robot, and the restraint system remains undocumented. Each group must start from scratch, or rely on word of mouth to build on the experience of others. This paper focuses solely on the artificial restraint system for legged robots, with discussion of various design options and documentation of existing systems.

Keywords: Legged Locomotion, Restraint Systems

1. Introduction

Development of three dimensional walking and running robots often begins in two dimensions with a boom or a planarizing mechanism. This artificial restraint system senses the robot's location in space, catches the robot when it inevitably falls, and simplifies the initial control development. The most common robot restraint system, a boom arm with a central pivot point, constrains the robot to the surface of a sphere-like shape such that while runs in a circle. With a long enough boom arm, this arrangement is a good approximation of running in a straight line. However, for smaller spaces or a better approximation, a true planarizing device may be a better option, despite the added complexity of using a treadmill or a very long track.

This paper provides a brief survey of artificial restraint systems used by current legged locomotion projects and details the design choices made during their construction. The restraint system subassemblies detailed in this paper include booms, pivot joints, counter balances, robot restraints and catches, data collection and transmission devices, planarizing systems, overhead restraint systems, and alternative stability systems. Projects documented in this paper include the BowLeg Hopper, Planar Biped, Thumper, MABEL, ARL Monopod II, ATRIAS, HRP-2, ARGOS, and Dexter ^{Zeglin}(1999) ^{Hodgins}(1991) $^{Hurst\&Rizzi}$(2008) $Park et\ al.$(2011)$Park, Sreenath, Hurst\&Grizzle$ $Ahmadi\&Buehler$(2006) $Kanekoet\ al.$(2004)$Kaneko, Kanehiro, Kajita, Hirukawa, Kawasaki, Hirata, Akachi\&Isozumi$

Dungan(2010) *Blackwell*(2010).

For the purposes of this paper, walking will be defined as movement "at a regular and fairly slow pace by lifting and setting down each foot in turn, never having both feet off the ground at once" *Jewell&Abate*(2010). Running will be defined as "the presence of intervals of ballistic flight when all feet are off the ground" *Raibert*(1986). The "hopping" robots covered in this paper are included with this definition of running in mind.

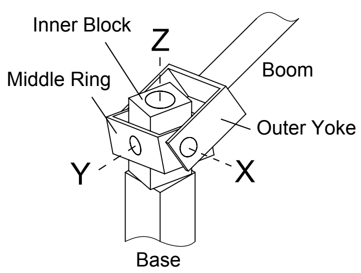
2. Restraint System Subassemblies

The most common method of constraining legged robots to two dimensional operation is a support boom, anchored to the floor, with the robot running in a circle around it. The different ways in which the pivot axes are aligned at the center of the boom will be covered in section 2.1. The different types of arms that link the robot to the pivot axis assembly are detailed in section 2.2. Some designs also incorporate methods of negating the weight of the boom arm or robot, such as a counterweight or spring attached to the ceiling. These designs will be covered in section 2.3. The methods used to stop or catch a robot that has lost its balance or is out of control will be discussed in section 2.4. Data collection and power transmission methods will be discussed in section 2.5, and planarizing restraints are covered in section 2.6. Overhead and alternative restraint systems will be covered in sections 2.7 and 2.8. A brief summary of three popular robot restraint systems will be provided in section 2.9.

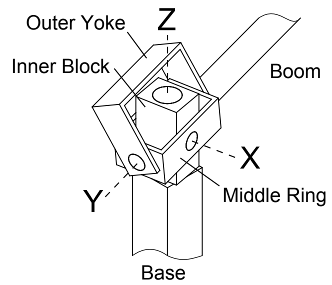
2.1. *Pivot Axes*

When a boom support is used, the robot generally runs in a full circle, and thus the vertical Z axis of the boom arm must allow full 360 degree rotation. The horizontal X and Y axes, which correspond to robot pitch and height, may not require this full range of motion, allowing for three basic gimbal arrangements shown in Figures 1(a) through 1(c). Sensors can be placed on all three axes to record angular position in all gimbal configurations. Advantages of each are somewhat dependent on the specific implementation, but in general, option 1(c) allows for convenient mounting of sensors and a good range of motion for the robot. Only option 1(c) will allow for somersaults or similar highly dynamic maneuvers.

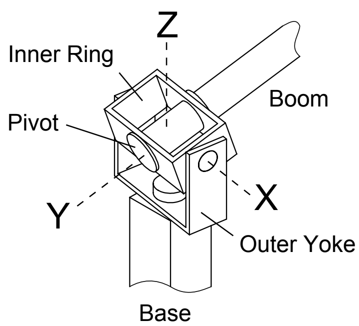
When hopping up and down, the robot follows a circular path as shown in Figure 2(a) and 2(b). Because the leg changes length when in contact with the ground, the toe necessarily will skid sideways, or the joint between the robot and the boom will flex. The height of the X axis determines the center of rotation for these approximately vertical excursions and affects the distance that the leg must skid along the ground. To minimize the lateral slipping of the toe, the X axis may be placed level with the ground, seen in Figure 2(a). When placing the X axis in this location, gimbal designs 1(b) and 1(c) cannot be used because the boom is not in line with the robot's pitch axis. In this case, the robot pitch joint (the Y axis



(a) 360° rotation about the Z axis, less than full rotation for X and Y axes.



(b) 360° rotation about the Z axis, less than full rotation for X and Y axes, but greater range than Figure 1(a).

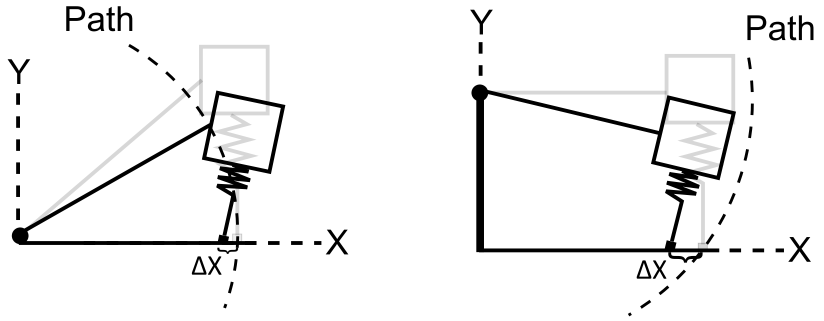


(c) 360° rotation about the Z and Y axes.

Fig. 1. Three basic gimbal configurations.

shown in the illustrations) can be moved off of the gimbal assembly and instead mounted between the boom arm and the robot with an angle between the joint and the boom. While this joint location adds weight to the robot, it has the advantage of simplifying the gimbal assembly.

In addition to lateral motion due to rotation about the boom's X axis, following a circular path about the Z axis also leads to lateral toe motion. The leg of the robot must extend directly forward, tangent to the circular path, with each stride; as the robot follows the circular path, the toe must slide inwards until it is on the circular path directly under the robot. Several solutions can be applied to this problem. For longer booms, some robots simply accommodate the lateral movement through flexing of the robot's legs, as was the case for the Planar Biped[Hodgins(1991)]. Others utilize small wheels as the point of the contact with the ground to allow radial rolling, as was done on Thumper, MABEL, and RABBIT [Hurstet al.(2008)Hurst,Chestnutt&Rizzi Grizzleet al.(2009)Grizzle,Hurst,Morris,Park&Sreenath Parket al.(2011)Park,Sreenath,Hurst&Grizzle]. Flexible joints, much like a hip joint, may



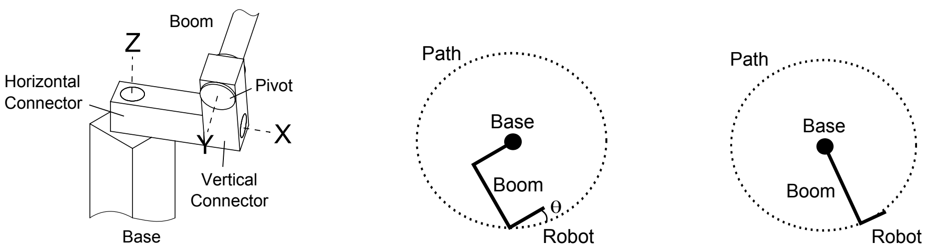
(a) The pivot axis joint assembly is placed level with respect to the robots foot. Note that the horizontal position of the robot's foot has not changed significantly.

(b) The pivot axis joint assembly is placed level with respect to the robots hip. Note that the large change in the horizontal position of the robot's foot.

Fig. 2. Effects of pivot axis assembly height.

also be used at the interface between the boom and the robot.

Offsetting the gimbal axes, as shown in Figure 3(a), can simplify the design of pivot axis assemblies. However, offsetting the Y axis from the Z axis will misalign the orientation of the robot with its path of travel, seen in Figure 3(b).



(a) (b) (c)

Fig. 3. By offsetting the boom from the vertical axis of rotation as in 3(a), the robot is not tangent to the circular path, shown in 3(b). Aligning the vertical axis of rotation places the robot tangent to the circular path, shown in 3(c), approximating a straight line as closely as possible.

Two final drawbacks common to all boom-arm restraint systems are that locomoting in a circular path will cause the outer leg of a bipedal robot to carry less weight and travel a slightly larger distance than the inner leg. These issues can sometimes be ignored, but may have a significant effect on some systems. Methods of lessening the effects of unequal leg travel are similar to those used to decrease lateral toe motion, discussed previously. In the case of Carnegie Mellon's Bowleg Hopper, the robot and restraint system were flexible enough to avoid any issues with unequal leg travel. This issue is avoided completely when using a planarizer and treadmill or overhead gantry crane to restrain the robot.

2.2. *Boom Arm*

Existing methods of robot attachment to the pivot axis assemblies include single-piece boom arms and four bar linkages. When a single-piece boom arm is used to attach the robot to a central gimbal, the robot will travel over the surface of a sphere. As the robot hops, the vertical orientation of the robot will always stay tangent to the surface of the sphere, as seen in Figure 4. A common problem with support booms is flexing, which adds unwanted dynamics to the system, and corrupts sensor readings. Solutions include using large-diameter and very stiff carbon-fiber tubes, or using cable reinforcements. Three or four cables can be anchored at the ends of the tube, with a triangular or square spreader at the mid-length to hold the cables out. The cables form triangles that greatly stiffen the tube and increase the frequency of the first-mode vibration.

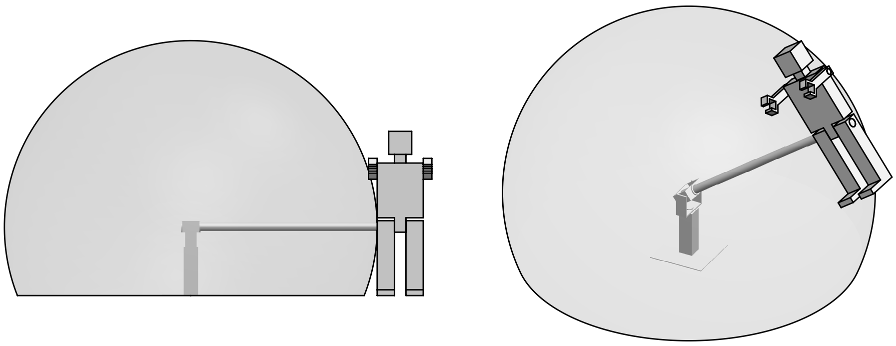


Fig. 4. Range of motion of a robot attached to the pivot axis point with a single boom arm. Note that the robot is always facing tangent to the sphere throughout its range of motion.

Lateral sliding of the toe on the ground can be a significant issue with short boom arms, and a four-bar linkage can improve the situation, allowing the robot to remain parallel to the vertical axis. The center of the robot no longer travels over the face a perfect sphere, instead traveling over a the face of a "compressed donut," shown in Figure 5. More complex linkage mechanisms could more closely approximate vertical motion for a relevant range of motion, and in some cases, the added complexity and mass may be a worthwhile trade.

2.3. *Gravity Compensation*

The weight and inertia of an artificial restraint system can significantly affect the behavior of a robot. Additionally, very heavy or underpowered robots may require

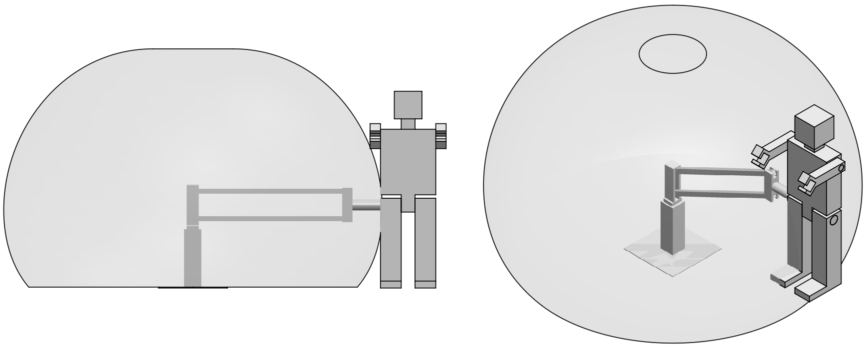


Fig. 5. Range of motion of a robot attached to the pivot axis point with a four-bar linkage. Note that the robot is always parallel with the vertical axis and that it no longer travels over the face of a perfect sphere.

gravity compensation to lessen the energy required to lift the robot off the ground. Two common methods of compensating for boom arm weight are the use of counter weights, or a spring attached to the ceiling.

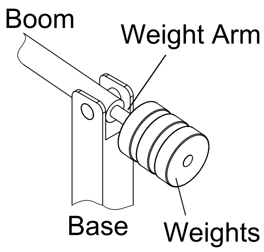
Using counter weights in the boom arm assembly, seen in Figure 6(a), is a simple solution but increases the inertia of the assembly and can change the dynamic behavior of the robot. In addition, counterweights may require a much stronger boom arm and base.

Using a rubber cord or spring attached to a pivot on the ceiling, seen in Figure 6(b), is a solution that does not add a large amount of inertia to the system. However, as the robot leaves the ground, the amount of weight compensation offered by the rubber cord or spring diminishes as the spring is shortened. To avoid changes in spring force due to spring displacement, a very long pretensioned spring, or "constant-force" spring, can be used. This spring is only displaced by a small percentage of its overall length during robot movement, and in turn does not significantly change the force it applies.

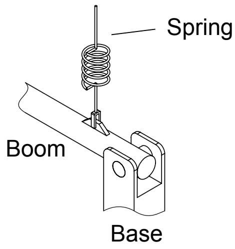
The counter weight, the spring, and the robot will all apply varying vertical forces as the angle of the boom arm changes. This may or may not cause problems, depending on the length of the boom. Neither design compensates for the inertia of the boom arm, which has the potential to significantly affect the behavior of the robot. The only solution for this is to minimize the mass of the boom.

2.4. *Robot Stopping and Catching*

In addition to constraining the robot's range of motion, the artificial restraint system must be able to catch the robot when it inevitably falls. Some smaller robots, such as the BowLeg Hopper, are simply damage-resistant due to foam blocks on the front and rear of the robot, and are allowed to fall. Others, including the



(a) Counterweights negate the weight of the boom arm but add extra inertia to the assembly.



(b) A rubber cord or spring attached to a pivot on the ceiling negates the weight of the boom arm while adding less inertia to the assembly.

Fig. 6. Counter-balancing methods.

walking robot Flame at TU Delft, are light enough that they can be caught by a human handler walking close by. Heavier robots, including Thumper and MABEL, rely on a cable attached to the ceiling that is long enough to remain slack when the robot is on its feet, but short enough to prevent the robot's knees from striking the ground. This method works well for robots that are light enough for a person to reset while heavier robots require a different robot catching method $_{Zeglin(1999),Hobbelen(2008),Hurst\&Rizzi(2008),Parket\ al.(2011)Park,Sreenath,Hurst\&Grizzle}$.

In the case of heavy robots, a powered capstan, seen in Figure 7, can be used. A powered capstan is simply a rope wrapped a few times around a drum, which rotates constantly with the rope slipping. One end of the rope is attached to a heavy load, and the other end is handled by an operator. When the operator pulls the rope taut, the friction between the rotating drum and the rope increases until the rope stops slipping, and the drum pulls the heavy load. In the case of some very heavy robots, a "robot wrangler" yanks on the rope when the robot falls, and the capstain lifts the robot upwards to avoid a crash[Raibert(2010)].

To limit the amount of shock felt by the robot as the cord becomes taut, it is advantageous to use a cord with a high level of elasticity. Climbing ropes are designed specifically to have a high level of elasticity and therefore have good shock absorption. Other nylon ropes have similar characteristics.

To prevent the application of large side loads at the point of connection between the robot and the boom arm, a second boom arm that rotates above the robot can be used as was done with Oregon State University's biped ATRIAS The stopping rope is connected to the end of this second boom and a vertical catch rope is connected between the robot and the second boom arm. This allows the weight of the falling robot to be slowed by a rope that is perpendicular to the robot instead of a rope that is connected to it at an angle.

In addition to limiting the height of the robot's center of mass, the rotation of

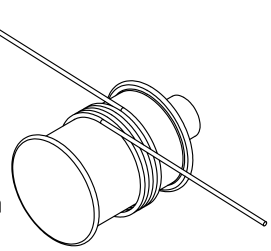


Fig. 7. Powered capstan. When the unloaded end of the chord is loose, the coiled rope slips over the constantly spinning drum. When the unloaded end of the rope is pulled tight by an operator, the friction between the coiled rope and the drum increases to the point where the rope wraps with the spinning drum, reeling in the load. Capstans like this are commonly used on nautical ships.

the robot must also be limited to prevent head strikes. The most simple method is to attach the rope to the top of the robot; however, this may apply large lateral forces if the rope is also tied to the center of the room. The pitch of the robot can also be limited internally, using stop blocks or other methods. While it is convenient to limit the pitch of the robot at the location of its rotation, maintenance can become an issue if the stops are difficult to access.

2.5. *Data Collection and Transmission*

Data collection for a 3D walking or running robot must be via inertial and gyroscopic sensing. Using a boom arm or other constraint device that is connected directly to the ground makes sensing much easier, and can be used as a ground truth system to test any inertial measurement units. Resolution of the sensor can be an issue for a boom arm, as the vertical excursion of the robot may lead to only a few degrees at the center of the boom. This is especially problematic when calculating the velocity or acceleration from a position sensor such as an optical encoder. However, because there is a very limited range of motion for the boom arm, a mechanical amplifier such as a gearbox or belt assembly can improve the resolution as long as it does not introduce backlash, belt stretch, or hysteresis.

Data can be transmitted to remote control units using cables with the aid of electrical slip rings. Electrical slip rings can be used at any point of rotation that would cause a cable to wrap around the robot, boom arm, or base. Slip rings offer complete freedom of rotation but may compromise signal integrity when damaged or worn. A more simple solution involves wrapping several revolutions of cable around the base of rotation and stopping the robot once the cable becomes unwound.

Data transmission over wireless devices has the obvious benefit of freeing the robot from any constraints caused by wired transmission. However, wireless data transmission suffers from several problems that wired data transmission does not. These include lost connections, slower data transmission rates and increased response latency.

Power can be transferred from external sources using either of the wired data transmission methods outlined above, through on-board batteries, or through a combination of both. Hydraulic and pneumatic lines can also utilize slip rings at points of line rotation.

2.6. *Planarizer and Treadmill*

The very first running robot used a simple planarizing mechanism, seen in Figure 8. The robot was placed on a table that was tilted up 10 degrees from the horizontal and moved over the table using ball bearings. Other similar robots have used air to reduce friction and allow movement when placed on an inclined plane by utilizing tables similar to those used for air hockey [Raibert(1986),Matsouka(1980)].

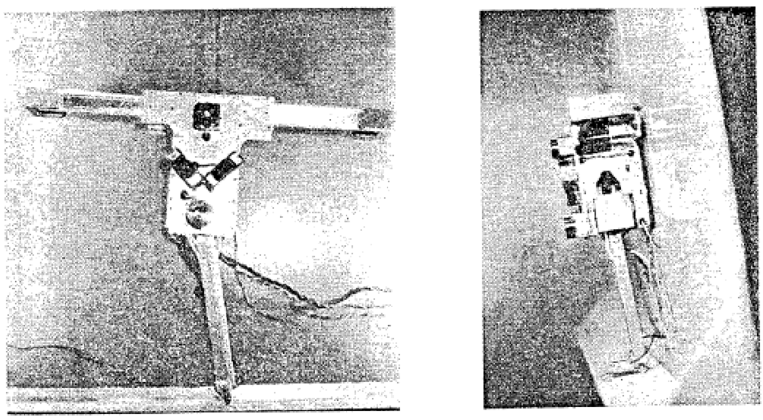
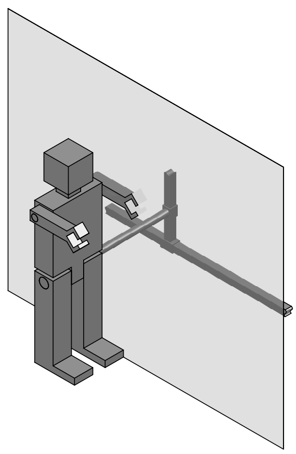


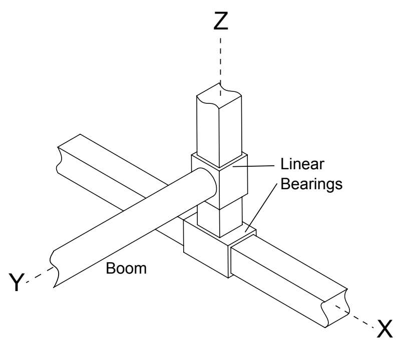
Fig. 8. Matsouka's running robot. Image from "A Mechanical Model of Repetitive Hopping Movements," used with permission from the Journal of the Society of Biomechanisms.

Variations of this design include combining a completely vertical planarizer with a treadmill so the robot walks and runs in place. This was briefly done at the MIT Leg Lab for a half-quadruped robot, using a 4-bar boom design to maintain vertical orientation, and at the Vrije University, Brussels for the biped Lucy[Krupp(2000),Vanderborghtet al.(2008)Vanderborght,Van Ham,Verrelst,Van Damme&Lefeber]. However, to minimize the effect of the treadmill on the dynamics of the robot, the treadmill must maintain a consistent speed despite impacts from the robot. A standard treadmill cannot provide this sort of consistency for large or heavy robots; anyone who has run on a standard treadmill is familiar with the sound of the belt decelerating and accelerating with each step. To prevent changes in treadmill belt speed, a good velocity control must be implemented. Large flywheels can be used to help minimize velocity variation, if necessary. The MIT Leg Lab used a powerful hydraulic treadmill for their experiments running in place. This adds another layer to the robot's control system because the speed of the treadmill must also be controlled to allow the robot to walk and run at different speeds $^{Brown(2010)}$.

As an alternative to a boom arm, a planarizing assembly with linear bearings constrains the robot to travel over the face of a rectangular plane, as shown in Figures 9(a) and 9(b). The ability of the linear bearings to accommodate translation in the horizontal and vertical directions negate the need for anything more than a simple pivot connection between the robot and the linear bearings. Advantages of this design include the elimination of the horizontal displacement of the robot's foot through its range of motion, lack of any centrifugal force as the robot runs in a circular path, and much smaller space requirements. Drawbacks include difficulty in sensing the foot reaction forces against the ground and difficulty in creating terrain variation such as bumps, changes in ground composition, or stairs. In addition, the linear bearings can affect the dynamics of the robot through friction and added mass. The sensing is not as convenient as on a simple rotational joint at the base of a boom arm, but may be more precise, due to the larger excursions.



(a) Range of motion of a robot attached to a planar pivot axis assembly. The robot travels over the face of a rectangular plane.



(b) Example planarizer assembly.

Fig. 9.

2.7. *Overhead Restraint Systems*

Overhead restraint systems can be used to catch robots that move in 3D and are not constrained to a lower dimensional space. Either overhead or rolling gantry cranes can be used to partially support the robot's weight and can be either actively or passively controlled. The use of overhead gantry cranes requires the permanent installation of overhead rails in a laboratory or room, while rolling gantry cranes are mobile and require no permanently installed assemblies. An example of an overhead gantry crane can be seen in Figure 10.

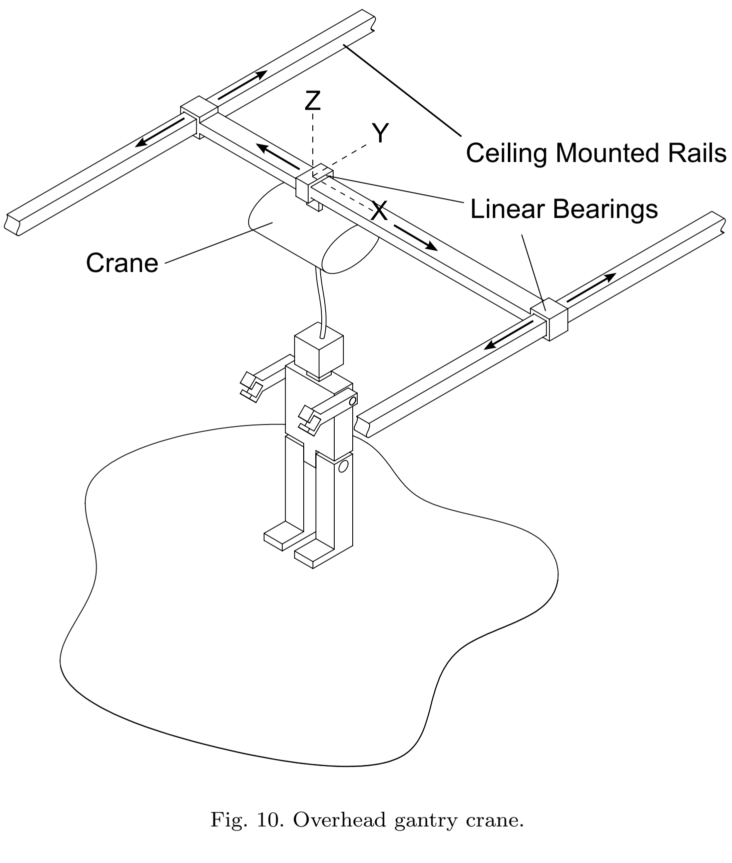


Fig. 10. Overhead gantry crane.

Active overhead restraint systems follow the robot using computer-controlled motors. A computer control system or human operator controls the crane and keeps it directly overhead of the robot, minimizing disturbances to the robot's motion. When the robot trips or loses balance, the crane stops and the restraining rope becomes taut, preventing the falling robot from hitting the ground. When maneuvering into position over the robot, the crane's speed and acceleration can affect the robot's motion and should be determined carefully.

Passive overhead support systems are either dragged forward by the robot or by human assistants. They are used by the Technical University of Munich and University of Tokyo and commercial robotics manufacturers such as Toyota, Honda, Tuskuba, and AIST. The crane can be easily brought into position over slow moving robots but could become troublesome to maneuver if attempting to keep up with running robots.

Both active and passive overhead restraint systems have the drawback of potentially limiting the height of the robot's range of motion. The size of the workspace is also a limitation for fast-moving machines. Only a few large strides are necessary to reach the workspace limits of most overhead gantry cranes.

2.8. *Alternative Stability Systems*

Several alternative methods for constraining robots to planar motion include the addition of symmetric legs, round feet, inner feet supports, or a moving lateral mass located above the hip. All methods allow the robot to move laterally without being tethered to its environment.

Symmetrical legs, seen in Figure 11(a), utilize two pairs of inner and outer legs to constrain the center of gravity and zero moment point of the robot to the sagittal plane. The symmetry of the design allows for robust lateral stability [Wisse(2004)].

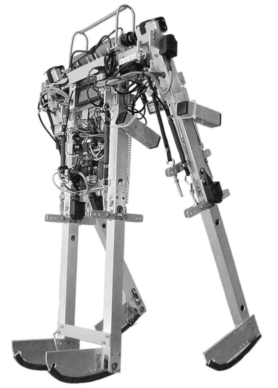
Rounding the bottoms of the robot's feet in a very specific manner, seen in Figure 11(b), causes the robot to produce a stabilizing side-to-side oscillation. This design provides dynamic lateral balance but results in a gait that can only be tuned to one forward velocity [Tedrakeet al.(2005)Tedrake,Weirui Zhang&Seung].

Small supports protruding from the feet of the robot, seen in Figure 11(c), create increased lateral stability by allowing the supporting area of each foot to overlap. This method changes the potential gait of the robot the least but does not allow the feet to be placed together[Gereckeet al.(2002)Gerecke,Albert,Hofschulte,Strasser&Gerth].

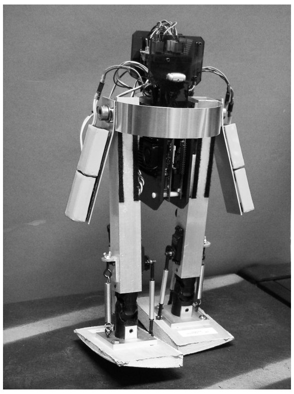
A moving lateral mass, seen in Figure 11(d), oscillates from side to side in sequence with the supporting foot. The increased weight over the supporting foot creates lateral stability[University(2010)].

2.9. *Summary*

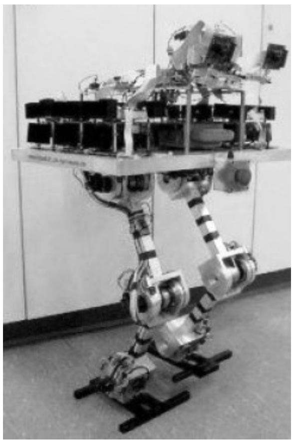
Figure 12 covers advantages and drawbacks for the foundation of three basic robot restraint systems: boom arms and gimbals, planarizers, and overhead gantry cranes. Generally speaking, if a large enough laboratory space is available, the boom arm and gimbal restraint system would be the simplest system to implement. If the laboratory space available is small, a planarizer and treadmill could be used. After the selection of a basic restraint system has been made, many more specific choices must be made.



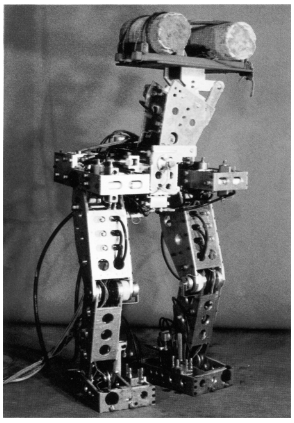
(a) Symmetric legs. Image from "Essentials of Dynamic Walking," used with permission from Martin Wisse.



(b) Rounded feet bottoms. Image from MIT's Robot Locomotion Group website, used with permission from Russ Tedrake.



(c) Feet supports. Image from "Analytic Path Planning Algorithms for Bipedal Robots Without a Trunk," used with permisison from Torsten Lilge.



(d) Moving lateral mass. Image from Waseda University's Humanoid Robotics Institute website, used with permission from Atsuo Takanishi.

Fig. 11. Alternative stability systems.

3. State of the Field

Artificial restraint systems used by existing legged locomotion projects including the BowLeg Hopper, Planar Biped, Spring Flamingo, RABBIT, Thumper, MABEL, ATRIAS, HRP-2, ARGOS, and Dexter are presented below. Further insight can be gained from the successes and limitations of each restraint system.

BowLeg Hopper and Planar Biped The BowLeg Hopper utilizes a single

Boom and Gimbal	
Pros	**Cons**
•Simple design •Easily modified terrain •Easy sensor mounting	•Spherical range of motion •Inner and outer legs travel different distances and support different amounts of weight •Lateral toe movement •Influence of centrifugal force and rotational inertia of boom arm assembly

Planarizer	
Pros	**Cons**
•Planar range of motion •Smallest footprint if used with treadmill	•Difficult to change terrain •Additional controls required with treadmill •Large footprint required without treadmill

Overhead Gantry Crane	
Pros	**Cons**
•Robot not restrained to any shape or plane •Easily modified terrain	•Large area required for fast moving robot •No restraint if robot not ready for 3D motion •May require permanent installation •Significant infrastructure required to implement

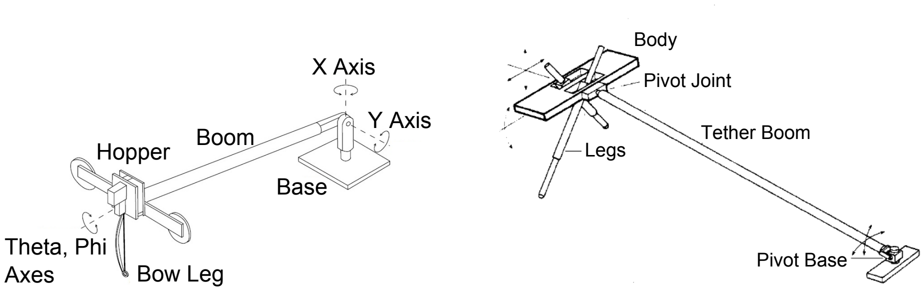
Fig. 12. Advantages and drawbacks of using a boom arm and gimbal, planarizer, or overhead gantry crane based restraint system.

boom arm, a 2D gimbal mounted to the floor like Figure 2(a), and a rotational joint that is in line with the robot's pitch axis, as shown in Figure 13(a) $^{Zeglin(1999)}$. The boom arm is slanted towards the ground and does not line up with the robot's pitch axis, requiring the robot pitch axis be mounted on the robot rather than at the base gimbal.

The height of the universal joint was designed to be as close as possible to the floor so that the leg was normal to the line between the toe and the pivot at the midrange of leg travel. This was done to minimize the radial distance traveled by the toe of the Hopper while the Hopper's leg compresses and expands during impact with the ground, as described in Section 2.1.

Additionally, the BowLegs boom arm uses an elastic rubber spring attached at approximately one third of its length to help reduce the weight of the boom arm and overall gravity that is felt by the Hopper. This rubber spring lessens the effect of gravity on the Hopper by about two thirds and helps make the robots gait slower and more easy to observe. While a counterweight could have been used, the added inertia was not desirable$^{Zeglin(1999)}$.

The Planar Biped, seen in Figure 13(b), also utilizes a base-mounted universal joint and single boom arm. As this robot uses hydraulic and pneumatic power from off board sources, slip rings are used to transfer pneumatic and hydraulic power through the boom arm and pivots to the robot[Hodgins(1991)].



(a) Diagram of the BowLeg Hopper. Notice the universal joint at the base of the assembly as well as the pivot at the hip of the hopper. Image from "The Bow Leg Hopping Robot," used with permission from Garth Zeglin and Ben Brown.

(b) Diagram of the Planar Biped. Image from "Biped Gait Transitions," used with permission from Jessica Hodgins and Ben Brown.

Fig. 13. BowLeg Hopper and Planar Biped.

Spring Flamingo and RABBIT Spring Flamingo and RABBIT, both bipeds that travel in a circular path, have similarly designed restraint systems[Pratt(2000),Chevallereauet al.(2003)Chevallereau,Abba,Aoustin,Plestan,Canudas−De−Wit&Grizzle]. Both utilize a central post-mounted simple boom arm, wheels on the feet of the robots (to allow for lateral toe slippage), and central 3D gimbal assemblies mounted at hip-height. These restraint systems allow for the robot to travel over the face of a sphere, as described in Section 2.2.

Both machines originally utilized counterweights to compensate for the added mass of the boom arm. However, due to boom arm flex, the counterweights were removed from RABBITs restraint system. Potentiometers at the center gimbal are used to collected data for Spring Flamingo while RABBIT uses absolute optical encoders. In addition, both machines use a cable tied to the ceiling, directly above the center post, to catch the robot when it falls.

An important difference between designs is the location of the pitch rotation joint: Rabbit uses a 3D gimbal at the center, while Spring Flamingo uses a 2D gimbal and places the pitch rotation bearings at the robot. The robots can be seen in Figures 14, 15(a) and 15(b).

Thumper and MABEL Both the monopod Thumper and biped MABEL, shown in Figures 16 and 17, use a simple boom arm and gimbal assembly that span the distance between the floor and ceiling[Hurst&Rizzi(2008),Grizzleet al.(2009)Grizzle,Hurst,Morris,Park&Sreenath]. A vertical beam is anchored at both the floor and ceiling with pillow block bearings, seen in Figure 18(a), allowing for 360 degree rotation. Although the beam itself is offset from the vertical axis of rotation, all three axes of rotation remain aligned, as seen

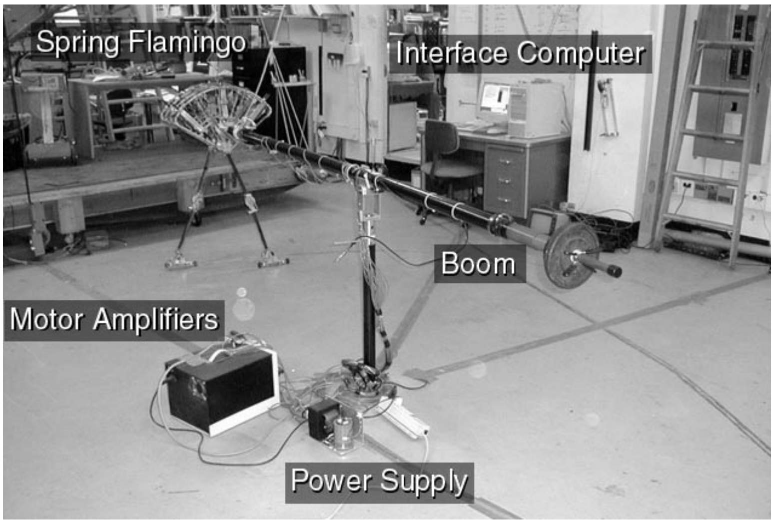


Fig. 14. Spring Flamingo. Image from “Exploiting Inherent Robustness and Natural Dynamics in the Control of Bipedal Walking Robots,” used with permission from Jerry Pratt.

in Figure 18(b). The boom arm is attached to the vertical beam with a pivot joint, such that Thumper’s boom is similar to the gimbal pivot axis assembly seen in Figure 1(a), but without the middle ring. Rather than a bearing at the base of the gimbal, the robot pitch is supported by bearings between the boom arm and the robot.

MABEL and Thumper require no gravity compensation as they support their own weight plus the low mass of the boom arm. A rope connected between the end of the boom arm and the top of the floor-to-ceiling pole prevent both machines from striking the ground during a fall. Because the pole rotates with the boom arm, the attachment for the restraint rope also rotates with the robots. The rope is loose during normal motion, but short enough to catch the robots before their knees strike the ground.

To limit the pitch of the robots and prevent head strikes, Thumper uses a secondary boom arm that extends from the vertical beam at approximately ceiling level, rotating with the robot. A rope connects to the top of Thumper, and prevents the robot from rotating more than approximately 90 degrees forward or backward. This boom arm prevents large side loads to the top of the robot when it falls. MABEL, in contrast, uses an internal hard stop and rubber block to limit pitch. This internal hard stop solution is an aesthetic improvement, eliminating the large structure that rotates with the robot. However, this design has lead to minor maintenance problems because the robot must be disassembled to access the hard stops.

Data is collected by absolute magnetic encoders placed at the bottom of the

(a) Rendering of RABBIT and boom arm. Image from "RABBIT: A Testbed for Advanced Control Theory."

(b) RABBIT, located at the GIPSA-Lab in Grenoble, France.

Fig. 15. Rendering and photograph of RABBIT. Note that the counterweights shown in the rendering were removed in operation to prevent boom arm flex. Both images used with permission from GIPSA-Lab in Grenoble, France.

floor-to-ceiling pole for rotation about the Z axis, at the connection point of the boom arm to the floor-to-ceiling pole for rotation about the X axis, and on the robot at the pivot between the robot and boom arm for rotation about the Y axis. Timing belts and pulleys are used to amplify rotation about each axis by an appropriate factor, such that the encoder turns slightly less than 360 degrees for the full range of motion of the boom.

One drawback to Thumper's boom arm system is unanticipated flexing of the vertical beam, which affected the Z axis sensing at the floor, interacted with the robot's control system, and caused oscillations. Adjustments and software filters were required to attenuate the oscillations.

ARL Monopod II ARL Monopod II is constrained to a 2D plane with a planarizer, shown in Figure 19, similar to the system outlined in Section 2.6 $^{Ahmadi(2010),Ahmadi\&Buehler(2006)}$. The robot is limited to vertical and horizontal translation and rotation about its hip, and travels over a two dimensional plane similar to that seen in Figure 9(a). Horizontal and vertical motion of the robot is measured by the use of rotational optical encoders and rack and pinion systems. The straight-line motion of the robot is accommodated by the use of a treadmill. A large servo motor, amplifier, and thin belt moving on a low friction surface min-

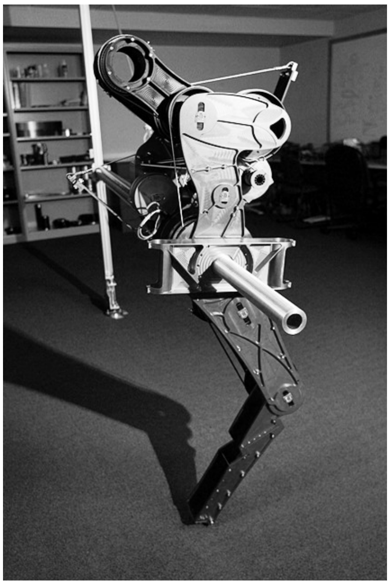


Fig. 16. Photograph of Thumper.

imizes the change in treadmill belt speed as the robot's feet contact and leave the belt's surface. The speed of the treadmill is set manually, or by the robot and a position feedback loop used to keep the robot in the center of the treadmill. While the addition of a treadmill affects the transient dynamics of the robot's motion, in steady state applications the robot's dynamics are similar to those of a robot traveling across a solid surface. A plot of the treadmill's desired velocity versus actual velocity can be seen in Figure 20 [Ahmadi&Buehler(2006),Ahmadi(1998)].

ATRIAS ATRIAS, a biped currently under development in the Dynamic Robotics Laboratory at Oregon State University, utilizes a simple carbon fiber boom arm, attached to a post at the center of the robot's circular path, for initial planar testing. The prototype boom is shown in Figure 21. Because of the light weight of the boom arm, no gravity compensation is necessary, thus saving the design from the added complexity and inertia of a counter weight or spring attached to the ceiling. The pivot axis assembly closely resembles the gimbal pictured in Figure 1(c) and was chosen for its simplicity and ease of manufacture.

An actuated joint between the robot and the boom handles lateral toe movement, rather than toe wheels or the inherent flexing of the robot leg. This joint is designed to act as a hip between the right and left leg, and in early development of the ATRIAS biped, the boom replaces the left leg. Data for the position of the robot is collected by absolute encoders placed on all axes of the gimbal, through appropriate mechanical advantages. The vertical Z axis has a 1:1 ratio, so the controller will know the position of the robot in the room; the pitch axis of the robot

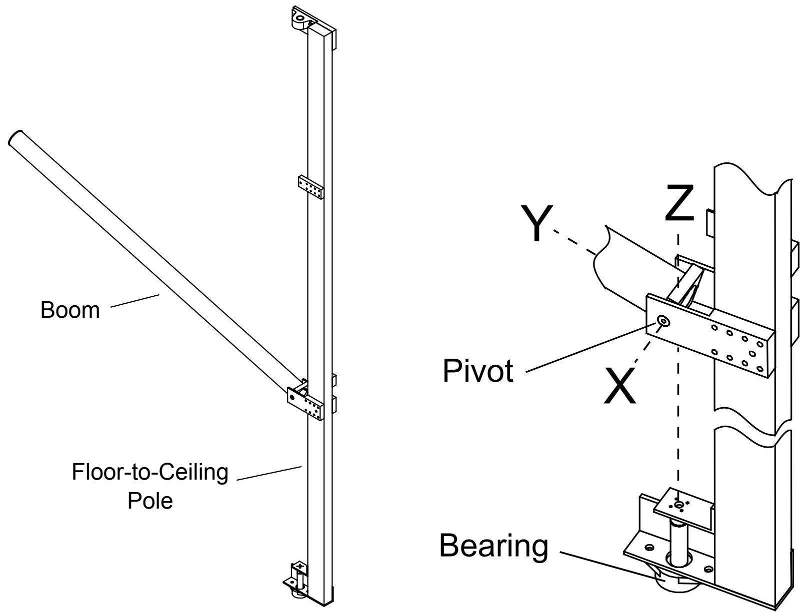
Fig. 17. MABEL bipedal robot, photograph courtesy Jesse Grizzle.

has a 2:1 ratio, because the robot is constrained to rotate less than 180 degrees, to avoid head strikes; and the height of the robot, or X axis on the boom, has a ratio of 10:1, maximizing the resolution of the absolute encoder through the small angular range of the height axis.

To avoid large side loads, a rotating upper boom arm is used. This upper boom arm modifies the angle of the ceiling mounted catch rope from connecting to the top of the robot at an angle of approximately 30° to 90°. Additional features of the restraint system include bolt together construction, adjustable boom arm height, and pulleys between the robot and upper boom arm for easier robot resetting.

HRP-2 HRP-2 is a humanoid robotics platform capable of walking on uneven surfaces and righting itself after falling over. During the development of the HRP-2, an actively controlled overhead gantry crane was used to catch the falling robot. The overhead gantry crane was guided by assistants via joystick. If the robot fell, the overhead restraining rope become taut and prevented the robot from hitting the ground. A photograph of HRP-2 and its gantry crane can be seen in Figure 22 *Kanekoet al.*(2004)*Kaneko,Kanehiro,Kajita,Hirukawa,Kawasaki,Hirata,Akachi&Isozumi*.

HRP-2 is also sold with the SunLift electric hoist. The battery powered hoist is



(a) Assembly view of Thumper's artificial restraint system.

(b) Close up of Thumper's pivot axis assembly.

Fig. 18. Thumper's artificial restraint system.

pushed behind the robot by an assistant and is capable of catching the robot if it falls.

ARGOS ARGOS, or the Active Response Gravity Offload System, is used by NASA to simulate reduced gravity environments for astronauts through the use of an active overhead gantry crane system. The primary function of the system is to offload the vertical weight of the subject. Controlled motion of the horizontal axes is provided by electrical motors attached to friction drive wheels operating on the underside of the crane rails. The vertical axis is connected to the robotic or human load through a steel cable and shock absorber in series. To simulate reduced gravity, the crane is actively controlled to apply vertical forces to the robot or human. To maintain the purely vertical lifting force needed to simulate reduced gravity, the overhead crane follows the subject on the horizontal axes by sensing the angle of the wire connecting the subject to the crane. A photograph of ARGOS can be seen in Figure 23. [Dungan(2010)]

Dexter Dexter is a bipedal research robot created by Anybots Inc. A powered rolling gantry crane, seen in Figure 24, is used to prevent the robot from hitting the ground during a fall. The gantry crane maneuvers through the use of electric motors powering each rear wheel. These motors are controlled independently, allowing the gantry crane to turn as a tank would. The robot is lifted to a standing position

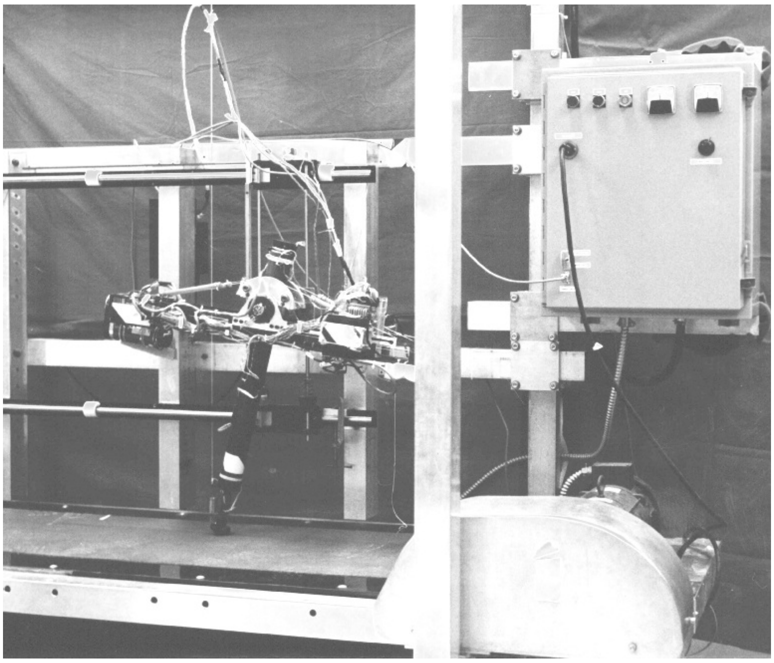


Fig. 19. The ARL Monopod II. Image from "Stable Control of One-Legged Robot Exploiting Passive Dynamics," used with permission from Mojtaba Ahmadi.

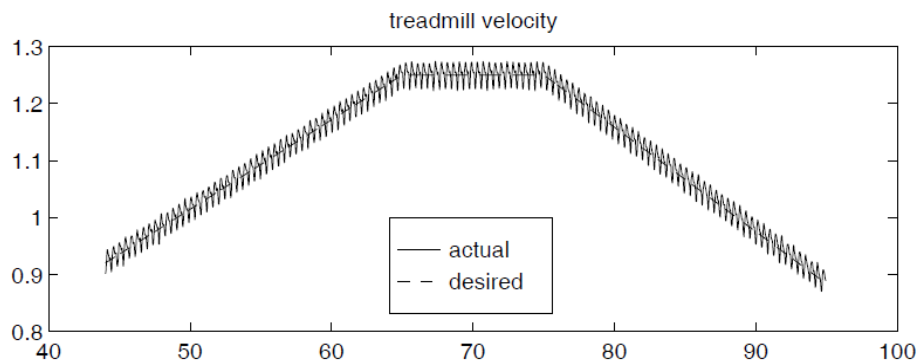


Fig. 20. Plot of desired versus actual ARL II treadmill speed. Image from "Stable Control of One-Legged Robot Exploiting Passive Dynamics," used with permission from Mojtaba Ahmadi.

through the use of a pneumatic lifting cylinder.

Initially, the position of Dexter's gantry crane was autonomously controlled to follow the robot and always remain overhead. However, when the robot fell during experiments, the control system would attempt to position the crane over the falling

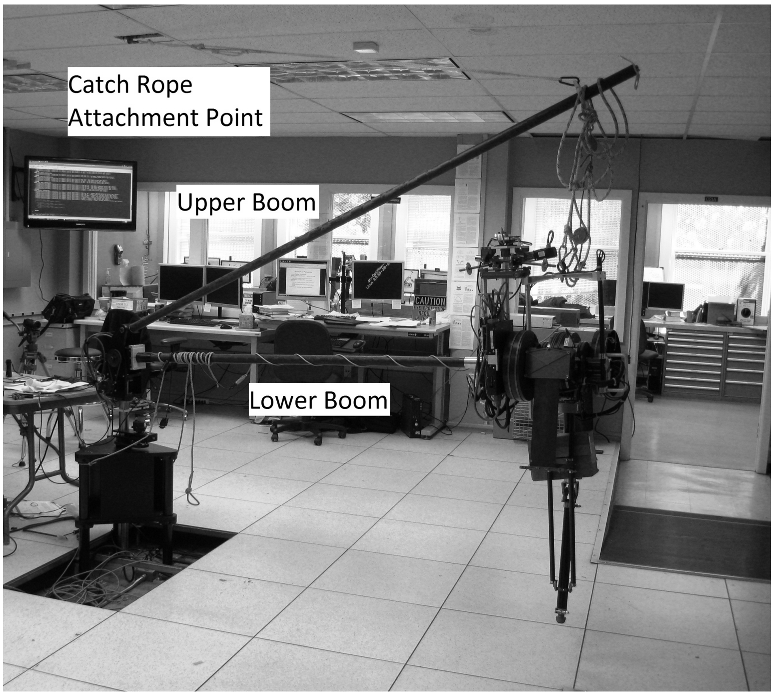


Fig. 21. ATRIAS' restraint system at Oregon State University.

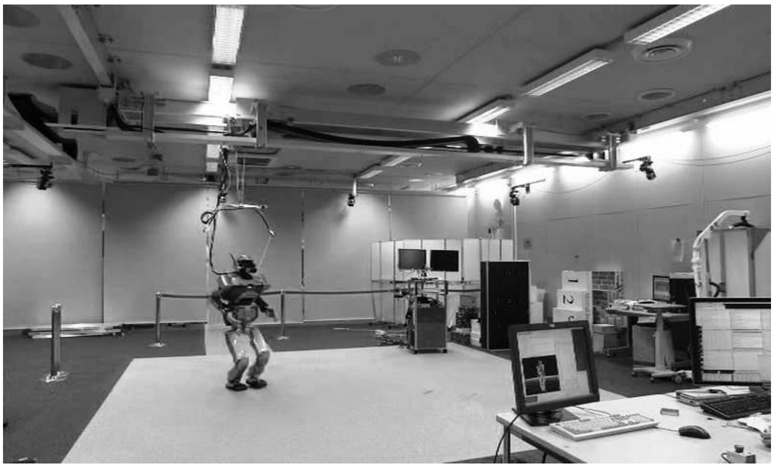


Fig. 22. Photograph of HRP-2 humanoid robotics platform with active overhead gantry crane restraint system. Photograph courtesy of Satoshi Kagami, DHRC, AIST.

robot, causing the crane and robot to accelerate quickly in the direction of the fall. To prevent this, the crane is currently controlled by an assistant via joystick.

Fig. 23. The ARGOS active overhead gantry crane. Photo Credit: NASA/JSC.

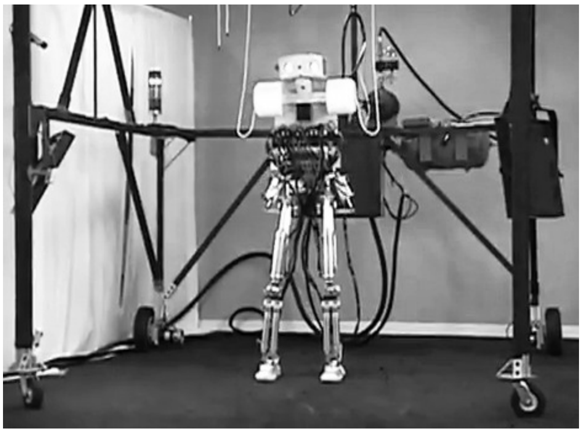


Fig. 24. Dexter humanoid robot and overhead gantry for 3D operation. Image from "Dexter 3.3 Walking Robot" promotional video, used with permission from Trevor Blackwell, Anybots, Inc.

4. Conclusion

While it is impossible for a single restraint system to be optimal in all settings, there is an interesting commonality among current artificial restraint systems that suggests some design choices may be better than others. The most common systems involve running the robots in a circle while tethered to a central post with a simple boom arm. As detailed earlier, this is the method that BowLeg Hopper, Spring Flamingo, RABBIT, Thumper, MABEL, and ATRIAS all use.

These designs are the simplest to build, offer a good platform for sensor mounting, and lend themselves to many existing solutions to the dynamic complications inherent in the system. While the robot will travel over the face of a sphere, causing radial displacement of the robot's foot, several measures can be taken to decrease this displacement. Examples include placing the pivot axis assembly at ground level, installing rubber wheels on the robot's feet, or adding a "hip" joint at the boom-leg interface. The added weight felt by the robot can be negated by springs, counterweights, or by making the boom arm of out a light weight material like carbon fiber. The ability of sensors to be placed on the boom arm or post facilitates data collection. These designs also allow the robot to travel on differing terrain by simply modifying the ground along its circular path.

A restraint system made up of a planarizer and treadmill may also be a viable alternative to restraining the robots to a circular path. This design has the advantages of requiring less space and limiting the robot's range of motion to a rectangular plane. However, a robust treadmill is required so that the changes in treadmill belt speed during the touchdown and liftoff of the robots foot will be negligible. This may be a problem for large and heavy robots. Additionally, the use of a treadmill complicates the creation of control systems. It is also very difficult to change the terrain on which the robot is walking or running. Considering all of the drawbacks, the planarizer and treadmill may be a less attractive system for many robots.

As the field of research in legged locomotion grows, so too will the creation of new artificial restraint designs. It is our hope that this document will be a useful first step in the design of new variations of booms, gantries, planarizers, and similar systems for a wide range of legged robots.

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