

# Design of a bipedal walking robot.

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## ABSTRACT

We present the mechanical design of a bipedal walking robot named M2V2, as well as control strategies to be implemented for walking and balance recovery. M2V2 has 12 actuated degrees of freedom in the lower body: three at each hip, one at each knee, and two at each ankle. Each degree of freedom is powered by a force controllable Series Elastic Actuator. These actuators provide high force fidelity and low impedance, allowing for control techniques that exploit the natural dynamics of the robot. The walking and balance recovery controllers will use the concepts of Capture Points and the Capture Region in order to decide where to step. A Capture Point is a point on the ground in which a biped can step to in order to stop, and the Capture Region is the locus of such points.

**Keywords:** Bipedal Walking, Humanoid, Force Control, Series Elastic Actuators, Capture Point, Capture Region

## 1. INTRODUCTION

To date, there have been a number of three dimensional bipedal walking robots developed, such as the Honda P2, P3, and ASIMO<sup>25,26</sup>, Sony QRIO<sup>27</sup>, Waseda University Wabian<sup>28</sup>, University of Munich's Johnnie<sup>29,30</sup>, Kawada/AIST HRP-2<sup>31,32</sup>, and others. Many of these robots are limited to commanding joint positions, rather than joint torques. This makes it difficult to perform complex tasks such as walking blindly over rough terrain, dynamically responding to unknown disturbances, or possessing the ability to capitalize on passive dynamic control strategies.

Yobotics is developing a twelve degree-of-freedom bipedal walking robot platform, which has been dubbed M2V2 (see Figure 1). The robot will be capable of high fidelity force control at each of the 12 degrees of freedom. With the ability to go beyond joint tracking trajectories, M2V2 will be used to implement, validate, and extend various bipedal control algorithms including those developed on Spring Flamingo<sup>1</sup>, a planar biped, and on a simulated three dimensional robot<sup>2</sup>.

We believe that high fidelity force control is a critical requirement for graceful walking over rough terrain and robustness to disturbances. Our previous work with the robot Spring Flamingo<sup>1,10,11</sup> has shown that good force control leads to simple yet reliable algorithms for walking over rolling terrain. Figure 2 shows time lapse photos of Spring Flamingo in 1999 walking over alternating 15 degree inclines and declines without any prior information or sensing of the terrain besides the location of where its feet fall. To date we know of no other bipedal walking robot that has been able to repeat this feat. We credit Spring Flamingo's graceful walking, in part, to the force-controllable Series Elastic Actuators<sup>33</sup> at its joints. An improved version of these actuators are used in M2V2.

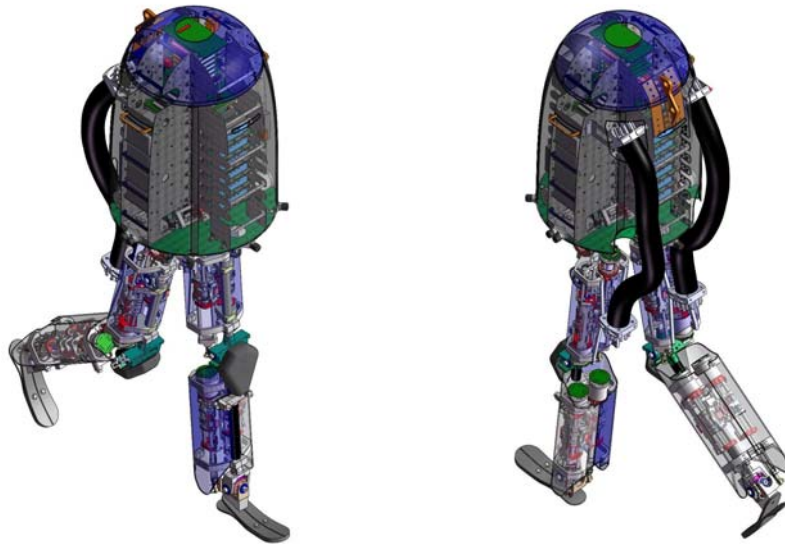


Figure 1: M2V2 is a 12 degree of freedom three dimensional walking robot, shown above in front and rear isometric views as designed in SolidWorks.

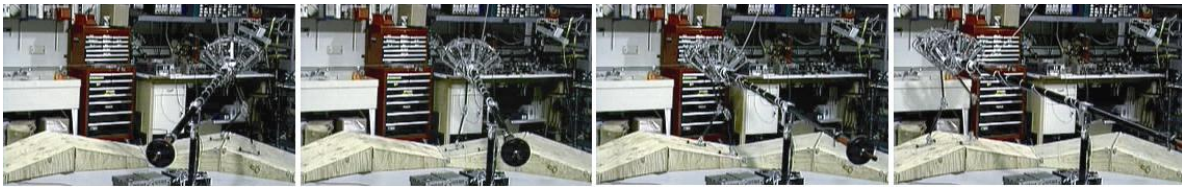


Figure 2: Spring Flamingo, a six degree of freedom planar bipedal walking robot. Successive images show Spring Flamingo walking over rolling terrain with no advanced knowledge of the terrain and only sensing it through ground contact with the feet.

## 2. DESIGN

### 2.1 Critical Specifications and Prior Work

A bipedal robot that is suitable for dynamic walking, balancing and push recovery (and to that end, capable of implementing Capture Points, Virtual Model Control, and Passive Dynamic elements) requires the following specifications:

- Three dimensional, with sufficient degrees of freedom to balance and walk three dimensionally.
- Force controllable. The actuators must be force controllable as all of our algorithms use force control at each joint. The required bandwidth is over 25 Hz for small forces and over 6 Hz for large forces. The required dynamical range is greater than 100:1.
- Mechanically and electronically robust, with a mean time between failures of several months.
- Possess an intuitive user interface with real-time feedback of state variables, easy entry of control parameters, easy means to capture and display data for debugging and documentation, and easy means to write, compile, download, and run software.
- Be integrated with a dynamical simulation environment so that control algorithms can be run interchangeably between the simulation and the real robot.
- Be easy to run and maintain. Ideally, operated by a single person.

M2<sup>34</sup>, which was developed at the MIT Leg Laboratory by Dan Paluska, Gill Pratt, and colleagues from 1996 to 2000, made strides toward these ambitious goals. However, typical of a first version prototype, the problems with M2 were

many including analog sensor noise, joint backlash, high stiction in actuators, complex and unreliable wire harnesses, unreliable and easily damaged analog force control circuits, time consuming and inaccurate joint homing routines, short battery life, difficult and time consuming assembly and maintenance, poor integration of simulated robot and physical robot, low computational power and a user interface with limited data acquisition.

M2V2, which utilizes a mechanical joint anatomy similar to its predecessor M2, is different in many ways. Specifically, M2V2 has:

- a new and improved version of the Series Elastic Actuator,
- improved mechanical design of most leg and body pieces,
- vacuum formed outer body shell to protect sensitive electronics,
- digital force sensors and digital position sensors mounted directly to the actuators,
- zero-backlash joints with ball bearings,
- carbon fiber foot with force sensing foot switch,
- snap-in lithium polymer battery packs,
- a new PC104 computer system with a Pentium processor operating at 1.4GHz with 1000Hz control loop,
- printed circuit boards with card edge connectors that eliminate most of the cable harnesses found on M2,
- new operating system that runs Real Time Java with real time GUI for development,
- and a simulation environment with seamless integration to the physical hardware.

## 2.2 Anatomy

M2V2 has twelve degrees of freedom consisting of three at each hip, one at each knee, and two at each ankle, a fairly typical arrangement for bipedal walking robots. The robot does not have any upper-body degrees of freedom as its main role is in bipedal walking research. The legs are made of carbon fiber tubes permanently bonded to machined aluminum components, which define the joint ranges of motion. The body of the robot is made of seven carbon fiber plates mounted orthogonally to one another (Figure 3). These plates provide a stiff structure for actuator mounting as well as a protective housing for the computer, motor amplifiers and batteries.

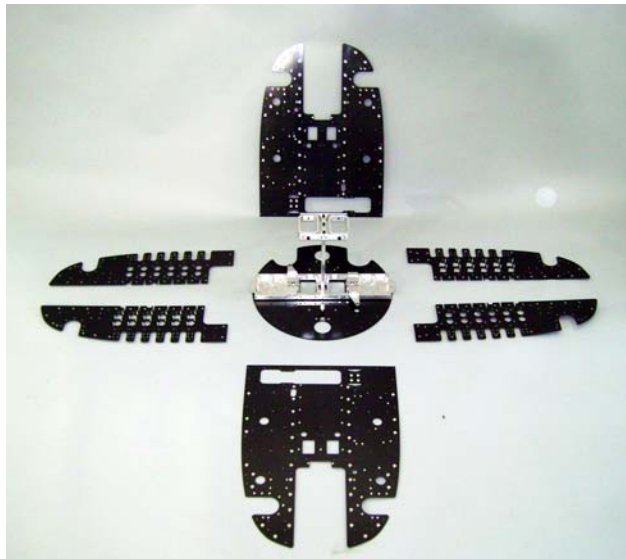


Figure 3: Carbon fiber plates unassembled. Seven plates bolt together at right angles to form the primary body structure which houses four of the 12 actuators (hip roll and hip yaw for both legs) as well as the electronics for the robot, including computer, batteries, motor amplifiers, and vestibular sensor.

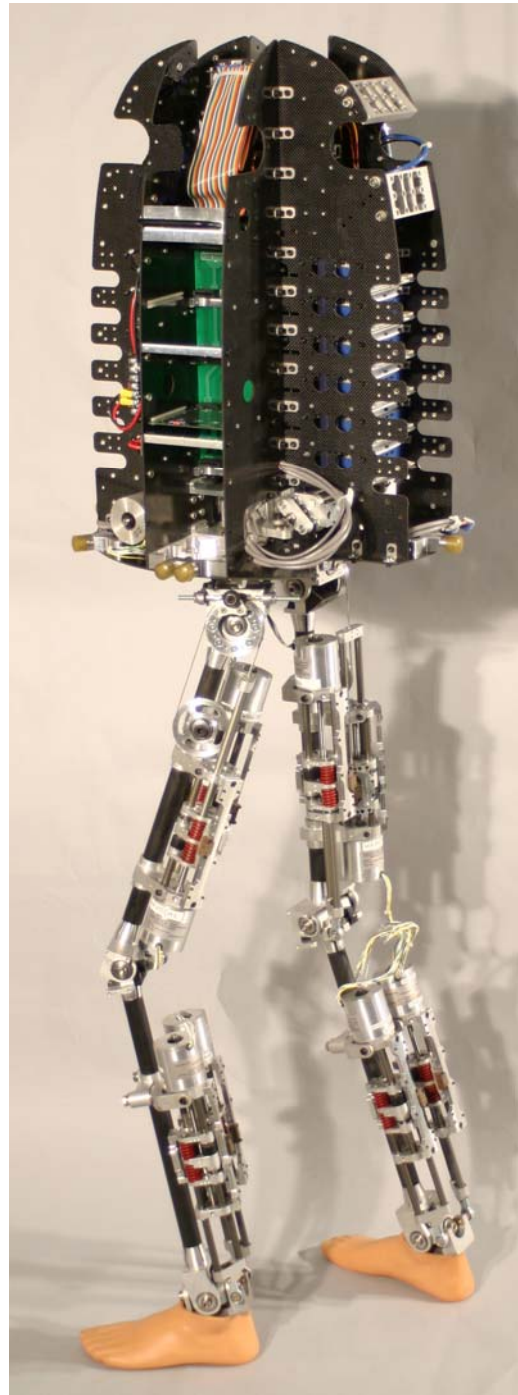
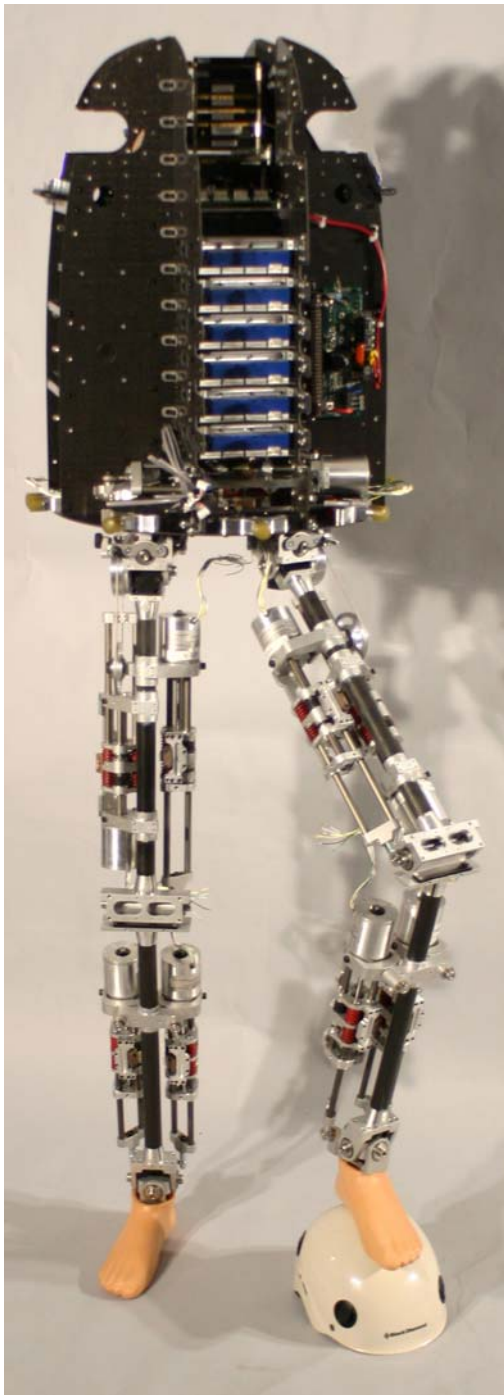


Figure 4: Front and side views of assembled robot body and legs. Not shown are batteries and cable harnesses to the 12 Series Elastic Actuators.

Table 1: Range of Motion

<b>Joint Degree of Freedom</b>	<b>Range</b>
Hip Yaw	$\pm 20^\circ$
Hip Roll	$+35^\circ, -15^\circ$
Hip Pitch	$+55^\circ, -25^\circ$
Knee	$+0^\circ, -90^\circ$
Ankle Pitch	$+20^\circ, -45^\circ$
Ankle Roll	$\pm 25^\circ$

Table 2: Robot Weight

<b>Robot Link</b>	<b>Weight</b>
Body, including computer, batteries, 4 actuators	61 lbs
Upper Leg, including 2 actuators	10 lbs (x2)
Lower Leg, including ankle, foot and 2 actuators	9 lbs (x2)
Total Weight	99 lbs

### 2.3 Actuators

The vast majority of walking robots today employ stiff position controlled actuators. The use of position controlled actuators results in the requirement of control algorithms that command desired positions, rather than desired forces to the actuators. This is unfortunate as such algorithms tend not to be robust to disturbances or rough terrain, usually require some sort of motion capture or trajectory generation engine. In addition these algorithms likely do not have desirable features of natural walking, as nature utilizes high-fidelity force-controllable actuators (muscle). Force controllable actuation at a robot's joints allows low impedance algorithms that result in efficient and graceful walking that is robust to disturbances and rough terrain. In addition, they allow the use of many of the mechanisms that are used in passive dynamic walking robots, such as a swing leg that swings freely as a double-link pendulum. For portions of algorithms that require position control, a force controllable actuator can easily be controlled as a position controlled actuator by servoing to desired position with feedback from the joint position sensors. M2V2 uses Series Elastic Actuators<sup>35</sup> to achieve force control.

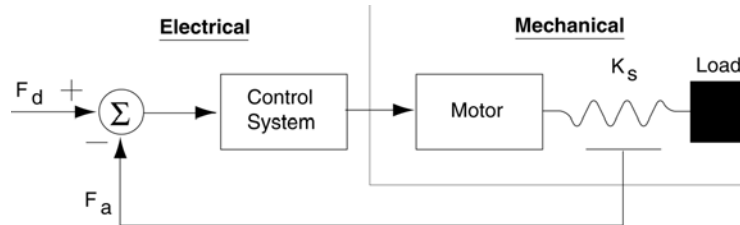


Figure 5: Schematic diagram of a Series Elastic Actuator. A spring is placed between the motor and the load. A control system servos the motor to reduce the difference between the desired force and the measured force signal. The motor can be electrical, hydraulic, or other traditional servo system.

Series Elastic Actuators are high fidelity force-controllable actuators that were invented by Gill Pratt and Matthew Williamson at the MIT AI Lab and have shown their utility in a number of legged robots<sup>35</sup>, robot arms<sup>36</sup>, orthotics<sup>37</sup>, and exoskeletons<sup>38</sup>. In Series Elastic Actuators, a spring is placed in series with the output of a motor and gear train. The output force of the actuator is then dependent on the compression of the spring, governed by Hooke's Law ( $F=kx$ ). By servoing the compression of the spring via feedback control, the output force is thereby controlled. Hence the spring turns a position controllable device, such as a motor and gear train, into a force controllable device. Figure 5 shows the architecture of Series Elastic Actuators. Note that Series Elastic Actuators are topologically similar to any motion actuator with a load sensor and closed loop control system. However, in Series Elastic Actuators the load sensing

element is much more compliant than a traditional load cell. This results in much lower output impedance and higher fidelity force control.

In contrast to traditional actuation methods, series elasticity introduces significant compliance between the actuator's output and the load, allowing for greatly increased force-control gains. Consider the case of a compliant spring between a linear actuator and rigid load. A moderate linear movement will generate a very small force reading. Thus, closed loop control gains can be very high while still ensuring the absence of chatter and presence of stability. Increased control gains greatly reduce impedance (increase back-driveability) and reduce the effects of stiction to give the actuators clean force output.

Compared to an actuator with a stiff force sensing element, Series Elastic Actuators have multiple benefits:

- The actuators exhibit lower output impedance and back-driveability.
- The dynamic effects of the motor inertia and gear train friction are nearly invisible at the output. In traditional systems, the actuator dynamics often dominate the mechanism dynamics, making it difficult to accomplish tasks that require high force fidelity.
- Shock tolerance is greatly improved by the spring placed in series between the drive train and the load.
- The force fidelity of the motor and the gear transmission is no longer critical, allowing the use of inexpensive motors with large torque ripple and gear reductions with relatively high friction.
- Force control stability is improved, even in intermittent contact with hard surfaces. Chatter is eliminated since a relatively large spring deflection is required to exert a small force.
- The actuator has lower passive impedance at high frequencies. Traditional actuators have impedance that resembles a large inertia (the motor's rotor inertia multiplied by the square of the gear ratio) at high frequencies. A Series Elastic Actuator looks like a spring at high frequencies, which is much more forgiving of collisions and other unexpected interactions.

M2V2's actuators are the latest SEA design, including integrated force and position sensing with quadrature encoders as well as a differential driver to reduce noise on the digital lines. Mechanically, the actuators have been redesigned with floating linear bushings. The floating design (achieved simply with o-rings suspending each of the linear bushings) prevents binding, especially at the ends of travel where manufacturing tolerances between adjacent parts becomes critical for proper alignment. The floating bushings have reduced assembly time of the actuators, as well as greatly improved the performance. The specifications of the Series Elastic Actuator used in M2V2 are shown in Table 3. The dynamic range is the ratio of the maximum output force and the lowest resolvable force. Series Elastic Actuators typically have dynamic ranges exceeding 300:1, and therefore enable high force-fidelity applications such as the proposed robot.

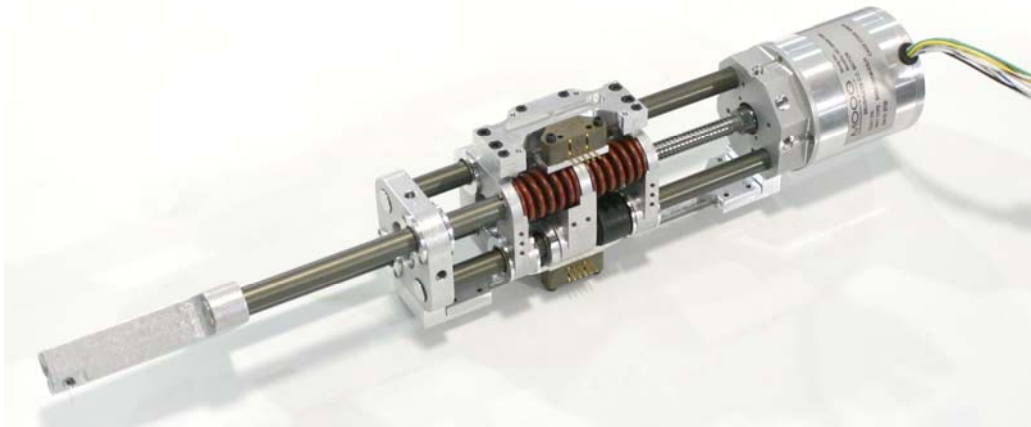


Figure 6: Photograph of Series Elastic Actuator for M2V2 with digital encoder force and position sensors and floating linear bushings.

Table 3: Specifications of Yobotics Series Elastic Actuator SEA23-23 used on M2V2

<b>Specification</b>	<b>SEA-23-23</b>
Weight	2.75 lbs
Stroke	3.3"
Diameter	2.3 in
Maximum Speed	11 in/s
Continuous Force @ Maximum Speed	127 lbs
Intermittent Force @ Maximum Speed	300 lbs
Smallest Resolvable Force	1 lb
Dynamic Range	300:1
Small Force Bandwidth	40 Hz
Large Force Bandwidth	10 Hz

## 2.4 Proprioception

M2V2 has 29 sensors which measure joint torques, joint positions, body orientation and rate of orientation and foot switch condition. The PC104 computer system reads each sensor at a rate of 1000Hz. The sensor inputs include:

- 12 actuator sensors measuring actuator force, from which joint torque is calculated.
- 12 actuator sensors measuring actuator position, from which joint position and velocity is calculated
- 1 inertial sensor measuring body roll, pitch and yaw and the rate of each.
- 4 foot switches monitoring the condition of the foot, either on or off the ground

## 2.5 Computer and Development Interface

The electrical system on M2 was somewhat problematic. Specifically, the cable harnesses required to connect the actuators, motor amplifiers, and computer system were a frequent source of failure due to wire fatigue. These connections are critical to the success of any experiment, as a single broken wire or even a single loose connection typically caused immediate failure. The task of tracking down an unknown failure point in the bird nest of wires was a daunting task. Figure 7 is a photograph of the robot showing the complexity of the wiring.

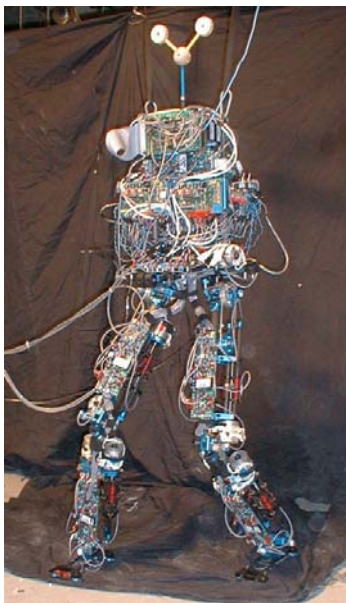


Figure 7: M2 in 2000. Note that analog control electronics for the actuators are distributed on the legs of the robot and a bird nest of wire harnesses were required to connect the actuators and sensors to the computer system.

In an effort to improve reliability and reduce assembly and debugging time, the computer system for M2V2 was designed to snap together using card edge connectors whenever possible. We arrived at a design which provided a PCB to PCB connection between the PC104 bulk head, batteries, ATX power supply and motor amplifiers. Ribbon cables were used to connect the PC104 bulk head to the PC104 mother board and each of the auxiliary PC104 boards (See Figure 8 and Figure 9). With this design, only 12 cable harnesses are required on the robot. The cable harnesses connect the Series Elastic Actuators to the motor amplifiers. Each harness carries quadrature encoder signals for force and position, as well as the motor hall sensors and motor power. The encoder signals are differentially driven at the source, thereby reducing electrical noise.

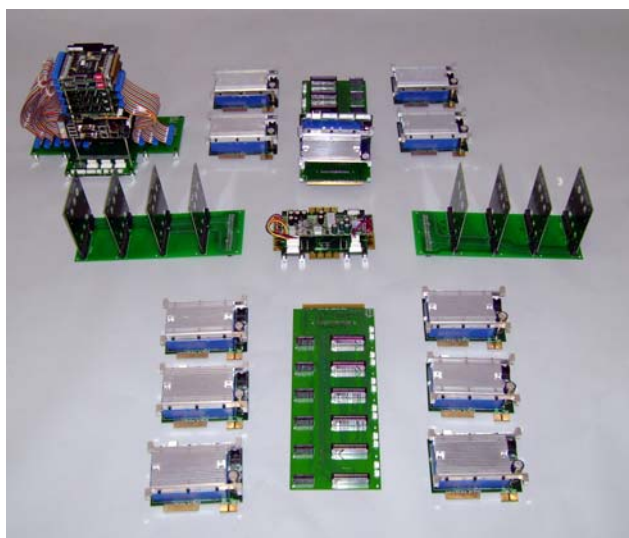


Figure 8: M2V2 PC104 computer system unassembled. Note the PC104 stack with ribbon cables in the upper left corner of the photograph. Batteries are not shown in this picture, but will be mounted with epoxy to the eight PCBs assembled vertically in the card edge connectors.

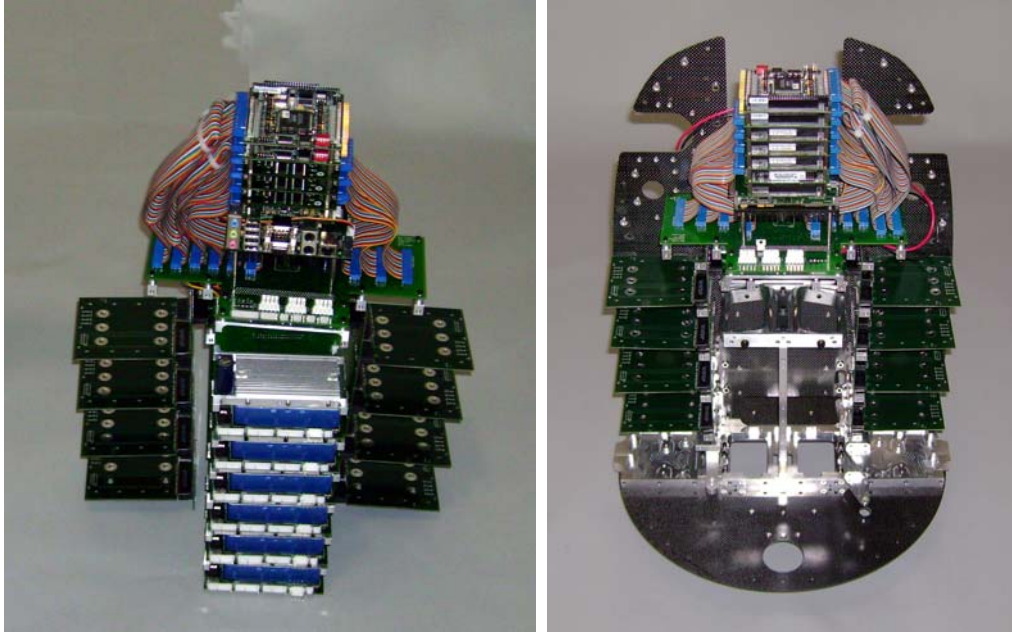


Figure 9: M2V2 PC104 computer system fully assembled on left. Photograph on the right shows the computer system in the context of the carbon fiber body plates, which provide structural support and protection.

The PC104 system runs Solaris 10 and Real Time Java, both available from Sun Microsystems. The control loop executes at 1000 Hz, reading the sensors of the robot and determining joint torques on each control cycle. The PC104 system consists of a number of stacked boards including the main processor, quadrature encoder-decoder boards for reading the encoders at the joints, and an analog Input-Output board for reading the inertial sensor, and a PWM output board for sending current commands to the motor amplifiers.

For development purposes, the on-board PC104 computer system communicates via wireless Ethernet to an off board PC. The off-board PC acts as a dummy terminal, providing a graphical user interface to interact with the robot. For example, as the robot walks, its control variables can be plotted in real time, along with a graphical representation of the robot at approximately 60Hz. This interface is implemented using Yobotics' Robot Construction Set™ software (see Figure 10). The software allows the user to easily display any robot state or control variable in real time, change control parameters on the fly, and quickly upload new compiled algorithms to the robot. If higher data resolution is required, the on-board computer has 256MB of internal RAM so that it can record several minutes of its state and control variables at a rate of approximately 1000Hz, to be analyzed later using the Robot Construction Set™.

Not only can the user can change control parameters through the graphical user interface, but also through a 32 channel MIDI slider board. Each of the 32 input channels is programmable such that any variable can be assigned to each of the channels and be given minimum and maximum values for the sliders. We have used this MIDI board with several of our current robots and have found that it significantly reduces the time required to tune and test a robot, which despite all intentions to the contrary, typically requires some manual tuning. Because the Robot Construction Set™ has an open Java API, it is also quite easy to add other interfaces including joysticks.

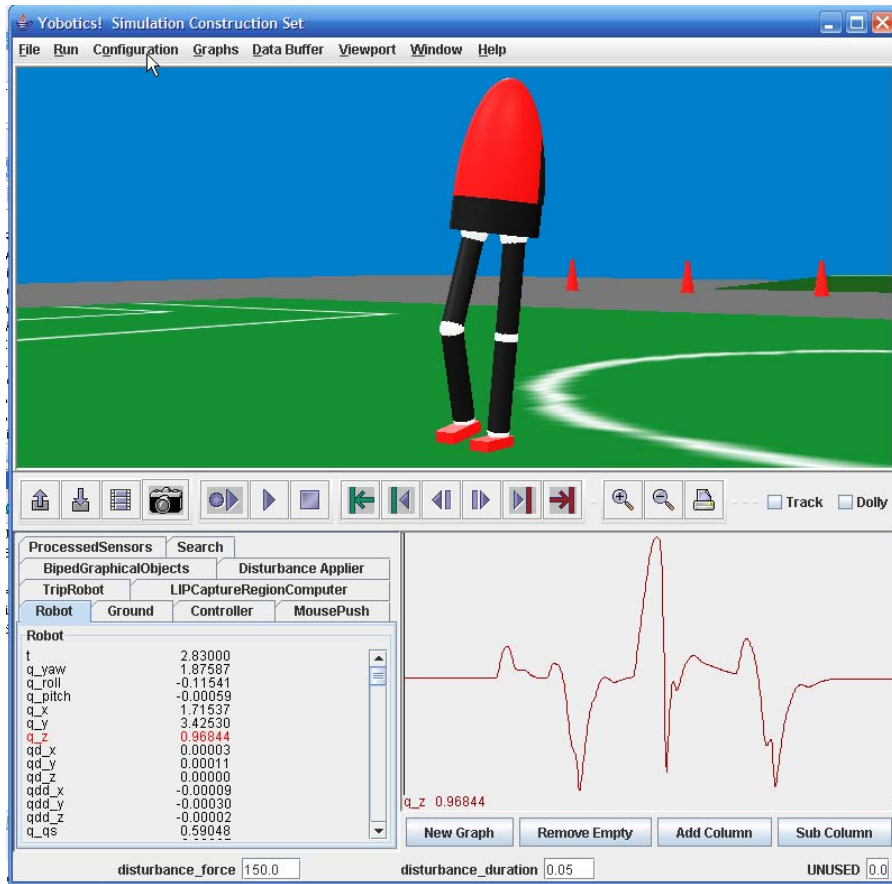


Figure 10: Screen shot of the Simulation Construction Set and the Robot Construction Set. The exact same software that controls the simulated robot also controls the real robot and the user input GUI is the same for both.

Finally, a powerful feature of the Robot Construction Set is that it integrates seamlessly with Yobotics Simulation Construction Set™. In this way, a researcher can develop algorithms on a simulated version of M2V2 (realistically modeled with accurate masses, link lengths, moments of inertia, torque slew rates, etc.) and then immediately try it on the real robot with no additional manipulation of the control code. Simulation code and robot code identically match.

### 3. CONTROL

Bipedal walking is difficult when viewed as a general dynamic system. The dynamics are high degree-of-freedom, non-linear, under-actuated, naturally unstable, and discretely change from step to step. These combined characteristics place bipedal walking control outside the realm of traditional “textbook” control techniques. It is in part due to these difficulties that a large number of different control methods have been developed, and no single method has proven advantageous over the others.

While legged locomotion seems to be a difficult problem when put in a traditional control framework, animals and humans make it look easy. Some animals, such as gazelles, can even run at high speeds within minutes of being born. Inspired by nature, we have searched for the characteristics that simplify the control of walking. First, the task of walking is inherently robust in that specific trajectories, precision, and repeatability are not critical. The resultant motion can vary considerably between individuals and even for the same individual from step to step. Thus, simple control strategies can often be used to control bipedal walking robots, despite non-optimal tracking performance. Second, the natural dynamics of the walking mechanism itself can be exploited in the control. This practice is highlighted by the work of the many researchers<sup>3-8</sup> in the passive dynamics walking community. Passive dynamic walkers can walk down small slopes with no internal energy source, relying on their dynamics and interaction with gravity in order to walk.

Based on the inherent robustness and natural dynamics of the walking mechanism, we have been developing control algorithms that are simple, decoupled, physics-based, and low impedance. These algorithms have resulted in graceful, efficient walking that is robust to rough terrain and disturbances on planar bipeds and on simulations of a 3D biped. The algorithms are relatively simple in that the control laws are typically linear and low order with a few simple terms. They are decoupled in that the control problem is decomposed into sub-problems, such as height, pitch, speed, and swing leg control, and independent controllers are developed for each part. They are physics-based in that the control laws and their parameters are physically meaningful and developed using physical intuition based on simplified physical models of the walking problem. They are low impedance in that the controllers are “soft” by using control techniques that do not require high precision and by keeping control gain parameters low whenever possible.

As an example of a control law used in some of our algorithms, we move the center of pressure on the foot based on the error in desired velocity. This control law is simple as it is a linear relationship; it is decoupled since it depends only on the robots forward velocity and not on any other state variables; it is physics-based as it is motivated by physical inverted-pendulum models of the support phase of walking and behaves in a physically sensible and understandable manner; and it is low impedance in that it does not depend on stiff position control of any degrees of freedom.

Inspired by the work of the passive dynamic walking research community, we have exploited the natural dynamics of walking in our walking algorithms by using the mechanisms of a knee joint limit, a compliant ankle, and passive swing leg. A knee joint limit simplifies height control and makes the resultant motion smoother and more efficient. Moving a joint to a limit and maintaining that position can be achieved with a very simple controller that exerts a constant effort in the direction of the limit. Without such a limit, maintaining a straight leg configuration during the support stance is equivalent to maintaining a system at a highly-unstable equilibrium point and hence is more challenging and can result in chatter if a high stiffness is desirable. A compliant ankle in a biped can naturally transfer the center of pressure forward on its foot as it walks forward. If tuned appropriately, as the robot moves forward, the ankle will rotate and the torque from the compliance in the ankle will cause the center of pressure to move forward with the center of mass. This benefit is achieved without requiring any computational control, and is efficient since applying the same torque with an ankle actuator would result in negative work being performed and absorbed by the actuator. The swing leg can swing passively forward, like a passive double-link pendulum once it is started. This simplifies the control and results in very natural looking walking.

Humans utilize each of these natural dynamic mechanisms during walking. They have limits at most of their joints, including their knees, enforced predominately through ligaments<sup>9</sup>. A human ankle behaves as a stiffening spring at approximately 15 degrees of dorsiflexion thereby naturally generating torque which moves the center of pressure on the foot forward as the center of mass passes over the foot<sup>9</sup>. Finally, during swing at slow and moderate speed, almost no muscle activity occurs in the swing leg<sup>9</sup>. It is likely that humans use other natural dynamic mechanisms in addition to these and part of our research is to discover such mechanisms and exploit them in the control of bipedal robots.

We have shown the utility of this approach on the Spring Flamingo robot and simulation of a 3D bipedal walking robot<sup>1,10-12</sup>. Spring Flamingo was able to walk gracefully and efficiently while being robust to external disturbances, such as being pushed. It could walk over ramp and rolling terrain with very minimal changes to its flat ground algorithm. The robot could walk at speeds up to 1.25 m/s, a moderate speed for a human of the same size. Our 3D simulated robot can currently walk at speeds up to 1.2 m/s and can catch its balance when pushed.

We are expanding these techniques to develop controllers for 3D bipedal walking that result in more robust and faster walking, dynamic turning, and walking over discontinuous “stepping stone” terrain. One innovation we are currently developing is the notion of a “Capture Point”<sup>2</sup>. We define the Capture Point as the point on the ground where all kinetic energy will be “captured” if the foot and center of pressure are placed at that point. Being able to estimate the location of the Capture Point, and place the swing foot in its vicinity is important for robustness to disturbances, such as pushes. It is particularly important in three dimensional walking, since both the direction and the distance to this point are important. As a consequence, having both feet on the ground is not a sufficient condition for balance, as it is in planar walking. We are developing various methods for estimating the Capture Point and strategies for placing the foot nearby. With these methods, our simulated robot has been able to “catch its balance” after being forcefully pushed, has been able to step to arbitrary locations, and has been able to weave through cones.

The algorithms we have been developing are partially enabled by the ability to produce torques at the joints of the robot, a capability that humans and animals possess and likely exploit. In particular, the benefits of a compliant ankle and a passive swing leg can only be achieved if the robot has low-impedance force-controllable actuation, as provided by Series Elastic Actuators on M2V2.

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