

Mechanical Engineering Challenges in Humanoid Robotics

by

Peter Guang Yi Lu

Submitted to the Department of Mechanical Engineering
in Partial Fulfillment of the Requirements for the Degree of

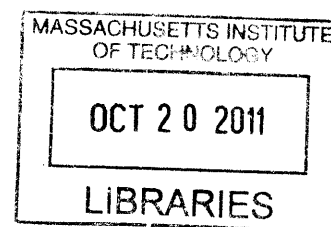
Bachelor of Science in Mechanical Engineering
at the
Massachusetts Institute of Technology

June 2011

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ABSTRACT

Humanoid robots are artificial constructs designed to emulate the human body in form and function. They are a unique class of robots whose anthropomorphic nature renders them particularly well-suited to interact with humans in a world designed for humans. The present work examines a subset of the plethora of engineering challenges that face modern developers of humanoid robots, with a focus on challenges that fall within the domain of mechanical engineering.

The challenge of emulating human bipedal locomotion on a robotic platform is reviewed in the context of the evolutionary origins of human bipedalism and the biomechanics of walking and running. Precise joint angle control bipedal robots and passive-dynamic walkers, the two most prominent classes of modern bipedal robots, are found to have their own strengths and shortcomings. An integration of the strengths from both classes is likely to characterize the next generation of humanoid robots.

The challenge of replicating human arm and hand dexterity with a robotic system is reviewed in the context of the evolutionary origins and kinematic structure of human forelimbs. Form-focused design and function-focused design, two distinct approaches to the design of modern robotic arms and hands, are found to have their own strengths and shortcomings. An integration of the strengths from both approaches is likely to characterize the next generation of humanoid robots.

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Chapter 1

Introduction

Humanoid robots are artificial constructs designed to emulate the human body in form and function. They are a unique class of robots whose anthropomorphic nature allows them to perform physical maneuvers, cognitive tasks, and social functions characteristic of humans. Their creation is often inspired by the aesthetic appeal of replicating the human form as well as the practical advantages of such a form in a world designed around the human body. The tools and environments of human civilization have been crafted specifically for upright bipedal walkers with two arms, two hands, and a head, physical features that humanoid robots share. Furthermore, humans are socially tuned to respond to humanoid forms, a product of both nature and nurture. Humanoid robots are thus uniquely suited to interact with humans in a world designed for humans.

Humanoid robots are also valuable research platforms for studying the human body and brain. The challenges of emulating the stable yet dynamic nature of human bipedal locomotion and matching the mechanical dexterity of human hands garner new appreciation for the physical capabilities of the human body. The challenges faced by artificial intelligence researchers in duplicating even the most elementary cognitive tasks performed by the three pounds of fatty matter that sits within the human skull underscore the deep complexity of the human brain. Efforts to emulate the human body and brain invariably require fundamental understandings of their form and function. The creation of fully functional humanoid robots would thus represent

not only a significant technological achievement but also a landmark in homo sapiens sapiens' understanding of themselves. They would be proof that humans know what humans are made of.

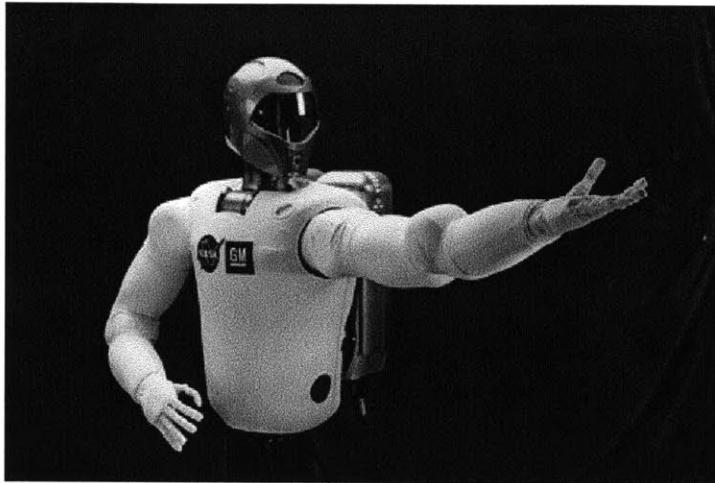


Figure 1: Robonaut 2, a humanoid robot designed by the National Aeronautics and Space Administration and General Motors for performing dexterous operations in space [38].

The present work examines a subset of the plethora of engineering challenges that face modern developers of humanoid robots, with an emphasis on challenges that fall within the domain of mechanical engineering. Past efforts to address these challenges will be reviewed, followed by surveys of successful modern advances and promising avenues for future progress. Chapter 2 will focus on the challenge of emulating human bipedal locomotion on a robotic platform while Chapter 3 will examine the complexities of replicating human arm and hand dexterity. Finally, Chapter 4 will conclude with a few remarks on the unique social implications of humanoid robots.

Chapter 2

Bipedal Robots

Bipedalism – terrestrial locomotion on two limbs – is an important means by which humans interact with the physical world. Bipedalism enables travel over rugged terrain, allows for the navigation of complex three-dimensional routes, and frees the arms and hands for non-locomotory tasks such as the manipulation of objects and gestural communication. The human body has evolved to be an efficient employer of bipedal locomotion and human civilization has in turn developed around the human bipedal form. Stairs, chairs, and ladders – many of the most common-place tools and environmental features in the modern world are designed specifically for upright bipedal walkers. It is thus crucial for a humanoid robot to achieve robust bipedal locomotion if it is to function effectively in a world designed by bipedal humans for bipedal humans.

2.1 Human Bipedalism

Bipedalism is a rare form of terrestrial locomotion amongst mammals. Only four groups of mammals employ bipedalism as their primary form of transport: macropods, kangaroo mice, springhare, and hominian apes. The last of these groups includes humans. Bipedalism is more common amongst other classes of terrestrial animals. The vast majority of birds travel on their rear limbs when earthbound and some species of lizards travel on their rear limbs when moving at high speeds. The majority of bipedal animals walk with their backs parallel to the ground, their heads extended forward, and their tails extended behind. Primate bipedalism however is

unique in that hominian apes walk nearly upright. Human bipedalism is distinct still in that humans walk completely upright without the use of tails [10].

From a biological standpoint, bipedalism offers several advantages. It raises an animal's head, which increases the animal's field of vision, enables access to food sources higher off the ground, and enables the traversing of deeper waters by wading. Bipedalism also frees an animal's forelimbs for non-locomotory survival functions. In primates and rodents, these liberated forelimbs – the arms and the hands – are used for the manipulation of food, tools, and other objects. In birds, these fore limbs – the wings – are used for flight. Travel speed on land is slightly slower in bipeds than in quadrupeds. The ostrich, one of the fastest bipedal animals on land, has a top land speed of approximately 65 km/h. In comparison, the cheetah, a quadruped and the fastest land animal, has a top speed of approximately 110 km/h [12].

The evolutionary origin of bipedalism in humans is highly debated. It is known that bipedalism evolved in humans well before the development of stone tools and the enlargement of the human brain and evidence of bipedalism has been uncovered in *Australopithecus* fossils dating as far back as 4.2 million years ago. Several hypotheses exist for the evolution of human bipedalism. One hypothesis posits that the freeing of the hands for object manipulation was the principal evolutionary driver behind bipedalism. Another idea suggests that habitat changes – specifically, an increase in the global prevalence of savanna and scattered forests – favored the increased mobility offered by bipedal locomotion. Yet another theory holds that bipedalism evolved as a thermoregulatory mechanism in adaptation to hotter environments, enabling improved convection and decreased exposure to the sun. Evidence exists in support of all these hypotheses, though no definitive conclusions have been drawn [29].

Regardless of the specific origins of human bipedalism, it is manifest that the human body has adapted to walking on two legs. Morphological changes to the human musculoskeletal system over the past four million years have been largely motivated by a drive for energy efficiency in bipedal locomotion. In comparison to other hominian apes, humans have longer legs with proportionally larger leg muscles adapted to support the entire weight of the body. In humans, leg length is on average 171% of trunk length. In contrast, this value is 128% in chimpanzees and 111% in orangutans. Humans also have larger knees and hip joints for improved body weight support, with a vertebral column closer to the hip joint that reduces the energy required for dynamic balancing. Human feet are also arched rather than flat as in early hominids, allowing for more energy efficient weight transmission during stepping. In addition, a slight forward bend in the lumbar region of the vertebral column and a slight backward bend in the thoracic region bring the center of mass of the human body directly over the feet, facilitating an upright posture [13, 36].

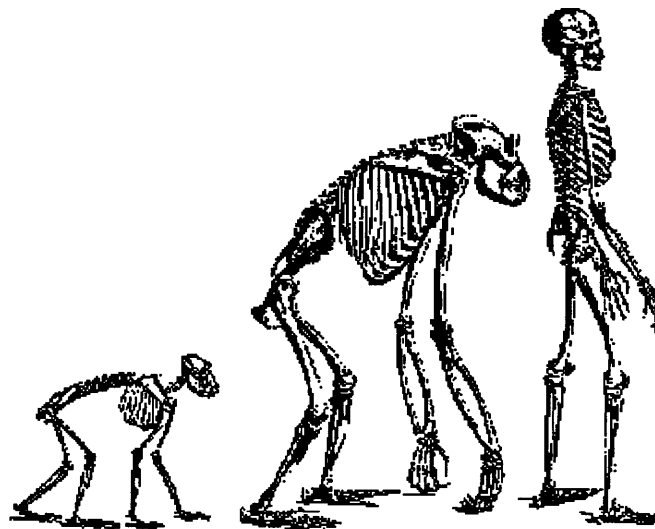


Figure 2: Bipedalism in hominian apes. From left to right: a chimpanzee skeleton, an orangutan skeleton, and a human skeleton [36].

2.2 Biomechanics of Walking and Running

Humans exhibit two principal modes of bipedal locomotion: walking, alternating use of the legs with one foot contacting the ground at all time, and running, alternating use of the legs with periods during which there is no contact with the ground. Of these two modes, walking is by far the most common as a means of basic transportation in the modern developed world. The average walking speed of an adult human is approximately 5 km/h, with human infants achieving basic walking capabilities by eleven months of age. Human bipedal walking can be characterized as alternating cycles of pendulum and inverted pendulum motions. During a step, the leg that is not making contact with the ground sweeps forward in a pendulum motion. Meanwhile, the leg that makes contact with the ground remains in an extended position while the body vaults over in an inverted pendulum motion, a form of directional falling. The sweeping leg then makes contact with the ground while the extended leg leaves the ground and the cycle is repeated. Forward kinetic energy is continuously interchanged with gravitational potential energy, with energy recovery arising principally from pendulum dynamics [30].

In contrast to walking, running does not feature an inverted pendulum phase but instead uses rapid leg acceleration to achieve temporary forward ballistic motion. Each stride in running features three phases: the support phase, during which the foot contacts the ground and the leg flexes at the knee joint, the drive phase, during which the leg extends at the knee joint, and the recovery phase, during which the foot leaves the ground and the hip rotates to drive the leg forward. In addition to the motion of the legs, significant upper body motion is involved as well to maintain rotational stability. Kinetic energy and potential energy increase and decrease in phase during running, with out-of-phase elastic energy storage taking place in tendons and muscles [30]. The energy expenditure of running per unit distance traveled is greater than that of

walking. Over a distance of 1600 m, a healthy adult human will expend approximately 1.4 times as much energy running at 10 km/h than he or she will expend walking at 5 km/h [16]. The fastest human footspeed on record is 44.72 km/h [23].

2.3 Early Efforts at Waseda University

Early efforts to emulate human bipedal locomotion on a robotic platform were made at Waseda University, Tokyo under the direction of Ichiro Kato between the years 1966 and 1984. During this time, the Kato Laboratory constructed a series of robotic leg pairs designed to emulate the alternating sweeping and vaulting phases of human walking. The first two models – model WL-1 and model WL-3 – were basic mechanical representations of human legs, featuring electro-hydraulic servo-actuators and open-loop control schemes. Model WL-3 was capable of coordinating between a swing phase, during which one of its legs would sweep forward in a pendulum motion, and a static phase, during which its other leg would remain stationary relative to the ground. The model's walking pattern was repeatable, but did not capture the dynamic inverted pendulum motion that is characteristic of human bipedal walking. In 1972, the Kato Laboratory completed model WL-5, which was capable of static walking with a turnover rate of 45 s per step and featured limited turning capabilities. Though it could navigate a simple trajectory on a flat surface, this model, like its predecessors, was restricted to moving its legs through carefully planned, stable physical states. It was perpetually balanced on the soles of its feet and lacked the dynamic nature of human walking [21].

The Kato Laboratory made significant advances in bipedal robotics between the years 1972 and 1984, culminating in the construction of model WL-10RD, the first bipedal robot in the world capable of dynamic walking. Whereas previous models had been limited to static walking,

model WL-10RD was capable of continuous bipedal locomotion through non-equilibrium states, a capability approaching the dynamic directional falling that characterizes human walking. The model was controlled by a 16-bit microcomputer and actuated by rotary-type servos at the ankles, knees, and hip. Torque sensors at the ankles and hip enabled basic feedback control and a laterally bendable upper body allowed for adjustments in center of mass. Model WL-10RD was capable of walking forward, backward, and laterally with a turnover rate of 1.3 s per step. It represented a major milestone in the field of bipedal robotics [21].

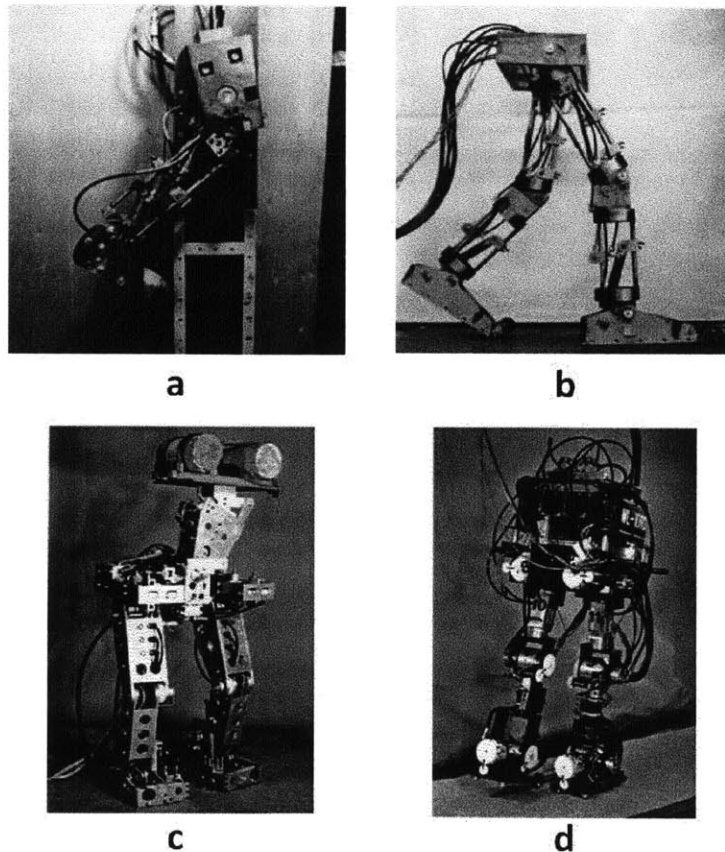


Figure 3: Early bipedal robots developed by the Kato Laboratory at Waseda University. a) Model WL-1 (1967); b) Model WL-3 (1969); c) Model WL-5 (1972); d) Model WL-10RD (1984) [21].

2.4 Early Efforts at Honda Motor Company

In 1986, the Honda Motor Company of Japan initiated its now world-renowned humanoid robotics research program, a program that would ultimately produce one of the most advanced humanoid robots in the world today, ASIMO. Honda's early research in humanoid robotics focused primarily on the problem of achieving anthropomorphic bipedal locomotion. The research group's first experimental models emphasized emulation of human physiology, with leg dimensions, weight distributions, joint placements, joint ranges of motion, and joint torque limits all specified based on measurements of the same parameters on the human body. By 1991, Honda's Experimental Model 4 was capable of dynamic walking on flat surfaces with a top speed of 4.7 km/h, comparable to the average walking speed of an adult human [20].

Research efforts turned next to developing control schemes for balancing while walking over uneven terrain, up and down stairs, and over obstacles. While a robot is in motion, the sum of the gravitational forces acting on the robot and the accelerations of the robot's components can be consolidated into a single vector originating from the robot's center of mass. This vector is known as the total inertial force vector. For the robot to maintain balance on every step, the intersection of its total inertial force vector with the ground – known as the Zero Moment Point or ZMP – must lie within the area over which the robot's foot contacts the ground. This condition can be maintained reliably for walking over flat surfaces but is more difficult to sustain when traversing uneven terrain. Small variations in slope within the region where the robot's foot contacts the ground can place the robot's ZMP outside of the stable zone, resulting in a tipping force [9, 25, 37].

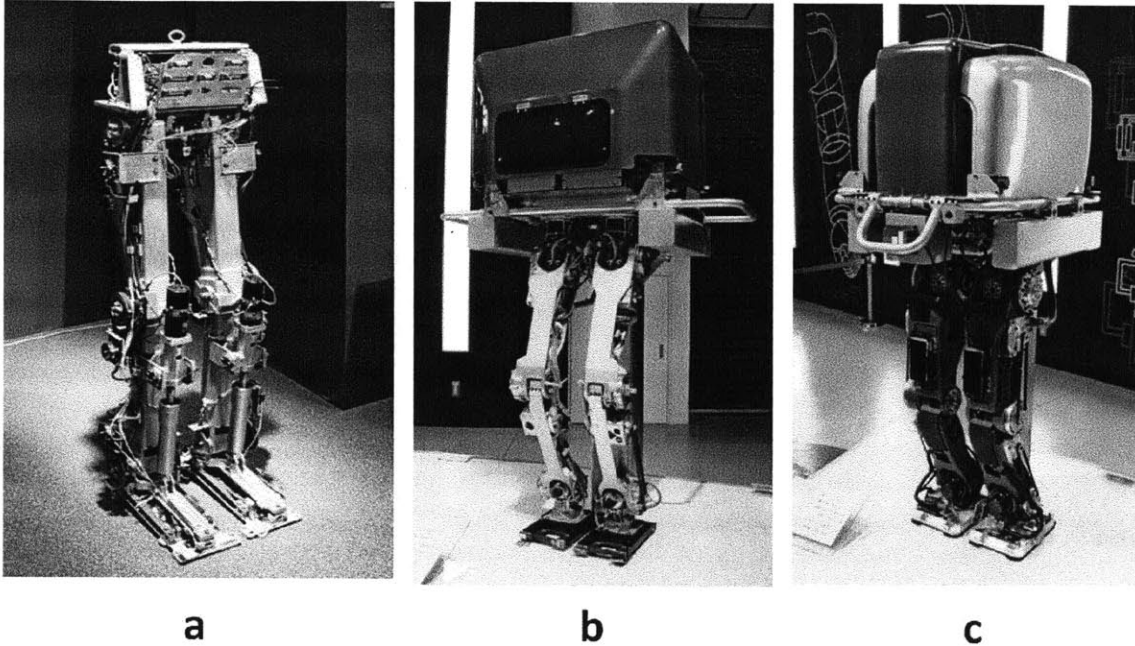


Figure 4: Early bipedal robots developed by the Honda Motor Company.
a) Experimental Model 0 (1986); b) Experimental Model 4 (1991);
c) Experimental Model 6 (1993) [20].

For its Experimental Model 6, Honda developed three control schemes to counteract such loss-of-balance conditions. The first control scheme employed floor reaction force response mechanisms at the ankle joints that directed the robot's feet to pronate in response to small deviations in the walking surface. This scheme was efficient and demanded little change to the robot's normal walking pattern but, due to the limited range of motion at the ankle joints, it could only handle a small set of balancing scenarios. The second control scheme involved a more complex feedback loop that employed angle sensors at the joints, accelerometers and a gyroscope at the hip, and six-axis force sensors at the feet to detect loss-of-balance conditions and to trigger a compensatory acceleration of the robot's upper body. The resulting acceleration would redirect the robot's ZMP back to within the stable zone and, if executed quickly enough,

would restore balance. The third control scheme was a look-ahead policy that was initiated in response to activation of the second control scheme. This last scheme would adjust the positioning of the robot's next step following the triggering of a compensatory upper body acceleration in order to maintain the desired stride length and walking speed. Together, these control schemes allowed Honda to demonstrate successful autonomous walking on stairs and slopes by 1993 [17, 18, 20].

2.5 ASIMO and Precise Joint Angle Control Bipedal Robots

The Honda Motor Company's latest humanoid robot ASIMO employs refined versions of the same control schemes originally developed for its Experimental Model 6. It features a total of twelve degrees of freedom in its legs, three at each hip joint, one at each knee joint, and two at each ankle joint. In addition, one rotational degree of freedom is present at the waist and a total of 21 degrees of freedom are present in the upper body, enabling highly responsive rotational stabilization during locomotion. Supplementing its basic walking stabilization control schemes, ASIMO employs a new high-level control scheme dubbed the i-WALK system that enables it to generate walking and turning protocols in real-time. Previous Honda models followed a set of predetermined discrete walking and turning protocols that were integrated in various combinations in order to create more complex behaviors. Though this paradigm allowed the models to navigate a variety of paths, it resulted in abrupt pauses in the robots' motion when changes in pace or sudden turns demanded rapid transitions between protocols. In contrast, ASIMO's i-WALK system enables flexible walking, whereby step cadence and feet placement are determined by the desired travel speed, the local terrain, and environmental obstacles. To

facilitate transitions between walking in a straight line and turning, ASIMO shifts its center of mass in the direction of the turn [20].

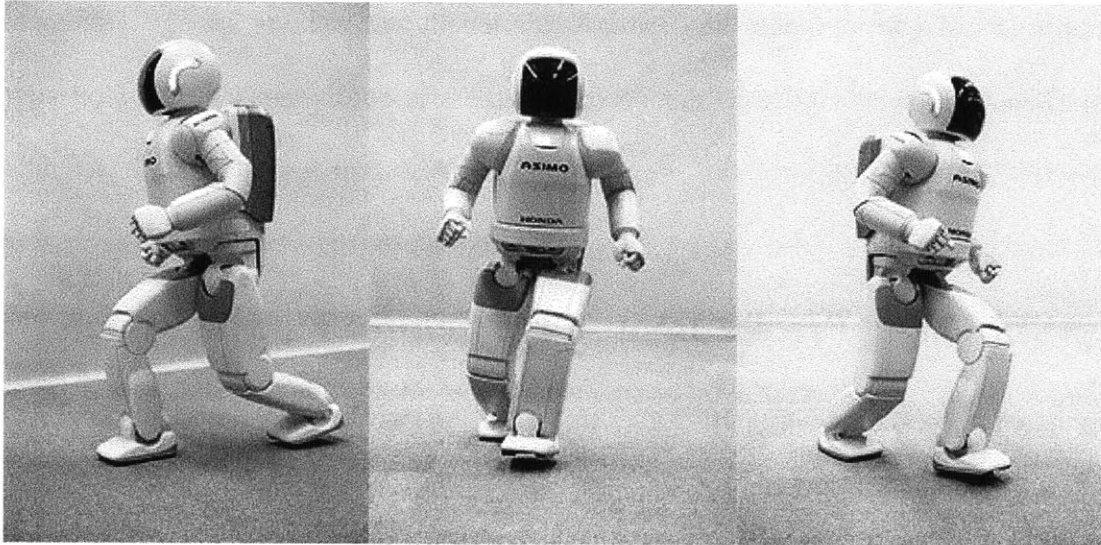


Figure 5: Honda’s ASIMO humanoid robot. ASIMO is capable of walking on uneven surfaces, climbing stairs, and running at speeds up to 6 km/h [20].

In addition to walking, ASIMO is also capable of bipedal running on flat surfaces. Its high-power motor drive units coupled with its light-weight legs allow for short step cycles of 0.32 s. The support phase and drive phase each constitute approximately 0.12 s of this cycle time while the recovery phase makes up the remaining 0.08 s. In comparison, the average adult human runs with a step cycle of 0.2 to 0.4 s, of which the recovery phase constitutes 0.05 to 0.1 s. ASIMO has a running speed of 6 km/h and a stride length of 525 mm. Upper body rotational stabilization prevents slipping during the beginning of the support phase and the end of the drive phase when ground reaction forces are minimal and mechanical compliance in the feet soles facilitates impact absorption. As in walking, ASIMO is capable of tilting its center of mass to facilitate running in a circular pattern [20].

ASIMO represents one of the most successful examples of a class of bipedal robots built with a design strategy known as precise joint angle control. Precise joint angle control bipedal robots are fully actuated at all degrees of freedom, which allows for the relative positions of their components to be controlled at all times. Other successful examples of modern precise joint angle control bipedal robots include the HRP-3 Promet developed by Kawada Industries and the National Institute of Advanced Industrial Science and Technology of Japan, Flame developed by the Biorobotics Lab of the Delft University of Technology, and Dexter developed by Anybots of the United States [14, 19, 26].

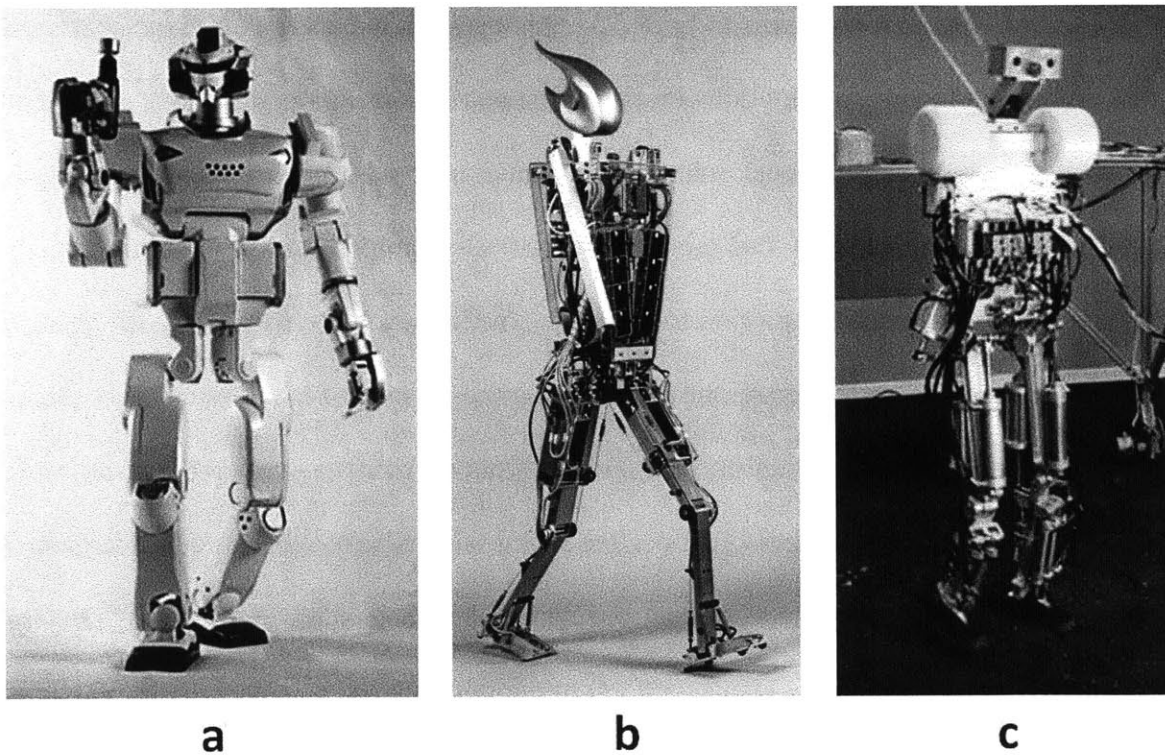


Figure 6: A collection of modern precise joint angle control bipedal robots from around the world. a) HRP-3 Promet; b) Flame; c) Dexter [14, 19, 26].

Precise joint angle control robots, owing to their displacement-controlled nature, are capable of the most complex physical maneuvers of any bipedal robots but also demand the highest energy expenditure. The specific energetic cost of transport – the energy required to carry a unit weight a unit distance – of Honda’s ASIMO is approximately 3.2 while the cost of human walking is approximately 0.2 [7]. In contrast to precise joint angle control robots, humans are able to achieve high levels of energy efficiency in bipedal locomotion without sacrificing functional complexity.

2.6 The Cornell Walker and Passive-Dynamic Walkers

Another class of bipedal robots aims to bridge the gap between the energy efficiencies of human and robotic bipedal locomotion by drawing design inspirations from the passive-dynamic nature of human walking. These bipedal robots have consequently been deemed passive-dynamic walkers and represent some of the most mechanistically simple yet most anthropomorphic examples of robotic bipedal locomotion to date [7]. The idea of using passive-dynamic walkers as emulators of human bipedal locomotion was first proposed by Tad McGeer in 1990. McGeer developed a simple two-leg mechanism with three degrees of freedom – two at the knees and one at the hip – that could walk down a slight decline with a surprisingly anthropomorphic gait. The device did not use actuators, sensors, or control schemes, but instead relied on gravity power and the alternating pendulum and inverted pendulum motions of its two legs to move forward [31, 32].

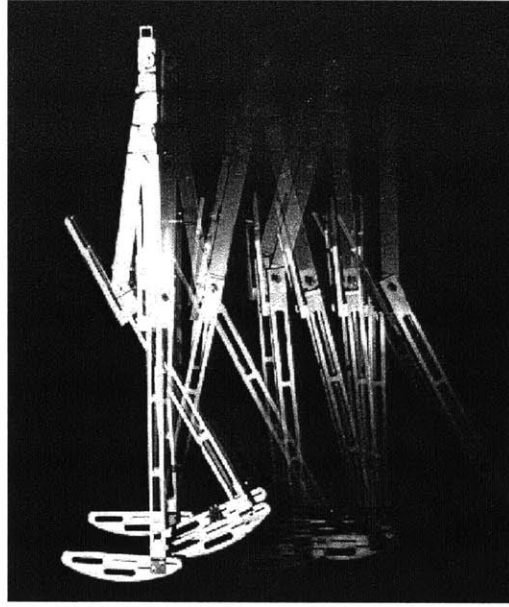


Figure 7: Tad McGeer’s original passive-dynamic walker at several stages of walking down a slight decline [32].

In the past decade, several research groups around the world have replicated and modified McGeer’s original gravity-powered walker to include small actuators at key joints so as to enable walking on level and inclined surfaces [7, 8, 46]. One such bipedal walker developed by the Human Power and Robotics Lab at Cornell University features five degrees of freedom – two ankle joints, two knee joints, and one axis connecting its two legs at the hip. The entire walker is mobilized by two actuators at the ankles, which alternately extend each of the robot’s feet when the other makes contact with the ground. Two force sensors at the feet provide the feedback signals necessary for step synchronization. The walker’s legs are latched at the knees to prevent hyperextension of the lower legs while both legs are unconstrained at the hip. This design allows the walker to move its legs forward by swinging them in a pendulum motion, significantly reducing its energy requirements. The walker also features two rigid arms that are mechanically linked to its legs, which provide rotational stabilization during walking. The entire

walker weighs 13 kg and consumes 11 W while walking at a speed of 1.5 km/h. Its specific energetic cost of transport is approximately 0.2, comparable to that of a walking human, and its walking gait is conspicuously anthropomorphic [8].

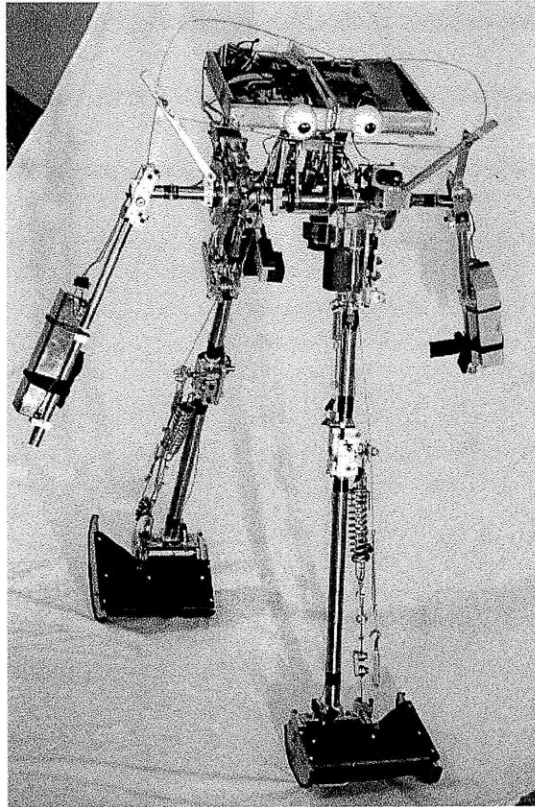


Figure 8: The Cornell bipedal passive-dynamic walker. The robot features five degrees of freedom but is only actuated at its two ankle joints [7].

2.7 Future Prospects

The Cornell bipedal walker, along with similar passive-dynamic walkers developed by research groups at MIT and the Delft University of Technology, have demonstrated the capabilities of simple, well-designed mechanical systems to achieve anthropomorphic bipedal locomotion [7].

The success of this paradigm of bipedal robotics suggests that advanced precise joint angle

control robots such as Honda's ASIMO may be able to achieve more anthropomorphic behavior through investigation and exploitation of their natural dynamics. Indeed, the human body itself uses a careful combination of natural dynamics and displacement control to achieve extensive functional complexity with high energy efficiency. An integration of the two leading concepts in bipedal robotics today – precise joint angle control and passive-dynamics – is likely to be a defining characteristic of the next generation of humanoid robots.

Chapter 3

Robotic Arms and Hands

The evolution of bipedalism in hominian apes enabled the successive evolution of forelimbs dedicated to object manipulation. In primates, the upper portions of the forelimbs are known as the arms and have evolved primarily for the spatial localization and mechanical support of the forelimbs' end effectors, the hands. Together, the arms and the hands are the principle means by which primates interact with objects in their immediate environment. For monkeys and apes, the arms and hands enable the manipulation of food, climbing, tactile social interactions, and gestural communication. For humans, this set of functionalities is expanded to include the use of tools, task-specific objects that extend physical capabilities. Cups, forks, pencils, door knobs, and keyboards – the vast majority of the devices used by humans day-to-day are designed to be manipulated by the hands. It is thus crucial for a humanoid robot to achieve versatile control of anthropomorphic arms and hands if it is to function effectively in a world designed by handy humans for handy humans.

3.1 Human Arms and Hands

The human arm is capable of achieving a wide range of motion due to the ball and socket joint that connects it to the torso, the shoulder. The upper arm bone, the humerus, is connected to the two forearm bones, the ulna and the radius, through a hinge joint known as the elbow. In addition to the single degree of freedom granted by the elbow, the ulna and the radius are also capable of a limited degree of relative rotation, allowing for pronation of the forearm. The

components of the arm are actuated by a series of antagonistic muscle pairs that enable the application of both contractile and extensile forces at every joint. Originally evolved for climbing in monkeys and apes, the components of the human arm are robust in tension, with the humerus capable of sustaining tensile loads of up to 1300 N [13].

The human hand is attached to the arm through the wrist, a joint with a significant range of motion in extension and flexion and a more limited range of motion in abduction and adduction. The human hand has five fingers, four of which are connected to the wrist through a series of four bones and three joints. The fifth, the thumb, is connected to the wrist through a series of three bones and two joints and has the unique capability of flexing in opposition to the other four fingers [13].

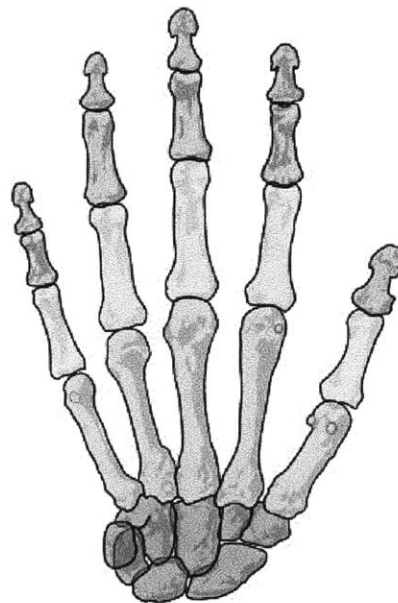


Figure 9: Skeletal structure of the human hand.

Flexion and extension at the joints of the hand can be performed largely independent of each other, leading to a plethora of possible hand configurations. Actuation of the hand is

achieved by two group of muscles, the intrinsic group and the extrinsic group. The intrinsic group consists of the smaller muscles of the hand whose muscle bellies are located on the hand itself. These muscles are responsible for the actuation of the outer two fingers – the thumb and the little finger. The extrinsic group includes the larger extensor and flexor muscles of the hand whose muscle bellies lie on the forearm. These muscles actuate the middle three fingers of the hand and are connected to the fingers by tendons that pass through the wrist. The fingertips of the human hand feature some of the largest densities of nerve endings in the human body and function as the primary sources of tactile information for humans [13].

3.2 Early Efforts at Waseda University

Concurrent with its seminal research efforts in bipedal robotics, the Kato Laboratory of Waseda University performed early work on the construction and control of anthropomorphic robotic arms and hands between the years 1967 and 1983. The Laboratory's first model WAM-1 featured 7 degrees of freedom, 4 in the hand and 3 in the arm, and was actuated by simple pneumatic artificial muscles made from rubber tubing that contracted when injected with compressed air. Though it did not feature any sensors or control schemes, the model demonstrated the efficacy of pneumatic artificial muscles for robotic actuation, an actuation scheme that would gain in popularity over the next four decades. The Laboratory's second model WAM-2 was completed in 1969 and featured a series of position sensors on the arm and hand as well as pressure sensors on the fingers of the hand. The artificial muscles of model WAM-1 were also replaced with better-understood electrical actuators in model WAM-2 and basic feedback control enabled the second model to grasp and transport small objects using its fingertips [21].

Between the years 1969 and 1983, the Kato Laboratory made several key improvements to its robotic arms and hands. Simple electrical actuators were replaced with more powerful electro-hydraulic actuators and torque feedback control was implemented through the use of strain gauges at every joint. Degrees of freedom were added and material strength was improved, expanding the range of executable maneuvers. Significantly, basic visual sensors were coupled with the internal position and force sensors of the Laboratory's robotic arms and hands, allowing for vision-guided manipulation. These improvements led to the creation of model WAM-7 in 1983, a robotic arm and hand pair featuring a total of 21 degrees of freedom, 7 in the arm and 14 in the hand. The fingers of model WAM-7 were flexed and extended by cables connected to actuators on the arm, analogous to the extrinsic muscles that actuate the human hand. The model could open doors, paint curved surfaces, and, most impressively, play a keyboard instrument at a rate of 15 keystrokes per second. Though the motor skills of model WAM-7 were largely pre-programmed, it was nonetheless an effective demonstration of the possibilities for robotic dexterity [21].

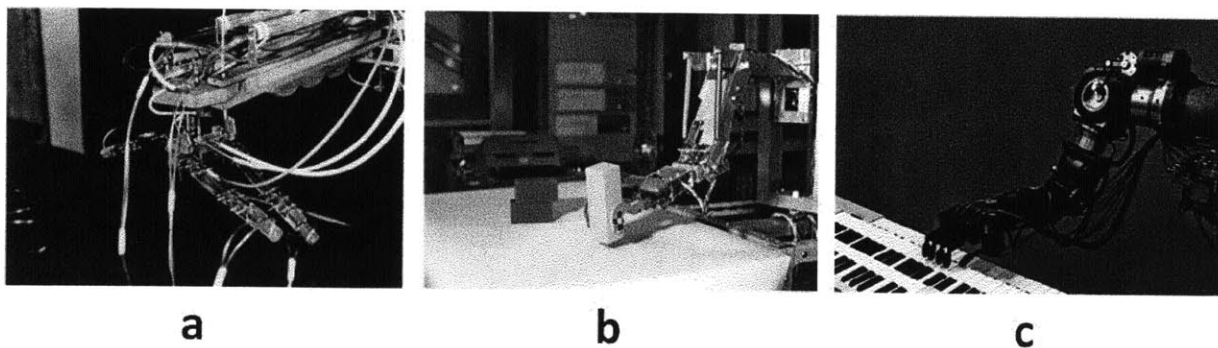


Figure 10: Early robotic arms and hands developed by the Kato Laboratory at Waseda University. a) Model WAM-1 (1967); b) Model WAM-2 (1969); c) Model WAM-7 (1983) [21].

3.3 The Shadow Dexterous Hand and Form-Focused Design

In terms of emulating anthropomorphic form, one of the most successful robotic hands in the world today is the Shadow Dexterous Hand developed by the Shadow Robot Company of the United Kingdom. The stated performance goal of the Shadow Dexterous Hand is to serve as a general purpose manipulator capable of operating in any capacity in which a human hand would be. In order to achieve this goal, the Shadow Dexterous Hand has been designed to closely match the physical dimensions and functionalities of the average human male hand. The current model, the C5 model, weighs 3.9 kg and features 24 degrees of freedom. A steel forearm bone supports an aluminum skeletal hand frame encased in a polycarbonate shell and a polyurethane textural coating [42].



Figure 11: The Shadow Dexterous Hand C5 developed by the Shadow Robot Company of the United Kingdom [42].

The Hand's kinematic structure is modeled closely after that of the human hand, with slight modifications that allow for reductions in mechanical complexity without concomitant limitations to functionality. The skeletal members incased within the human palm are emulated using a three-part palm structure capable of a comparable range of motion, while the thumb of the Hand is given an extra joint to compensate for any loss of dexterity caused by the modified palm. The ranges of motion of the Hand's joints are limited to those of the corresponding joints on the human hand. Basic joint coupling is also implemented on the Shadow Dexterous Hand. Specifically, the distal and middle finger joints are coupled such that the angle of the distal joint is never greater than that of the middle joint, as is the case for the human hand. Hall effect joint angle sensors are situated at every joint, with joint angles controllable to within 1° [40, 42].

The Shadow Dexterous Hand is actuated by 20 antagonistic pairs of pneumatic artificial muscles located in a pseudo-forearm structure beneath its wrist and connected to the moving components of the Hand by low friction wires routed through its wrist. These artificial muscles were developed by the Shadow Robot Company specifically to emulate the flexor and extensor muscles that actuate the human hand and are tuned with corresponding force limits and response times. Each muscle is capable of contracting up to 37% its original length, with maximum contractile force applied when the muscle is fully extended. The artificial muscles of the Shadow Dexterous Hand are thus ideally suited for applying large forces over short distances, similar to the muscles of the human hand. The muscles are made from rubber tubing wrapped with a high strength plastic weave and are highly flexible, allowing for bending around corners and curves, axial twisting, and stretching. Each muscle is equipped with a solid-state pressure sensor that is correlated with force output for force feedback control. The power-to-weight ratio of the muscles can be as high as 400:1, significantly greater than the 16:1 ratio common for

pneumatic cylinders and DC motors. A 6 mm diameter artificial muscle weighs 16 g and has the strength of a human finger muscle, while a 30 mm diameter unit weighs 80 g and has a maximum lifting capacity of 70 kg. The response times of the artificial muscles are comparable to those of human hand muscles and, used collectively, the muscles can open and close the Shadow Dexterous Hand in approximately 0.2 s. In sum, these pneumatic artificial muscles contribute significantly to the Shadow Dexterous Hand's high anthropomorphic functionality [40, 41, 42].

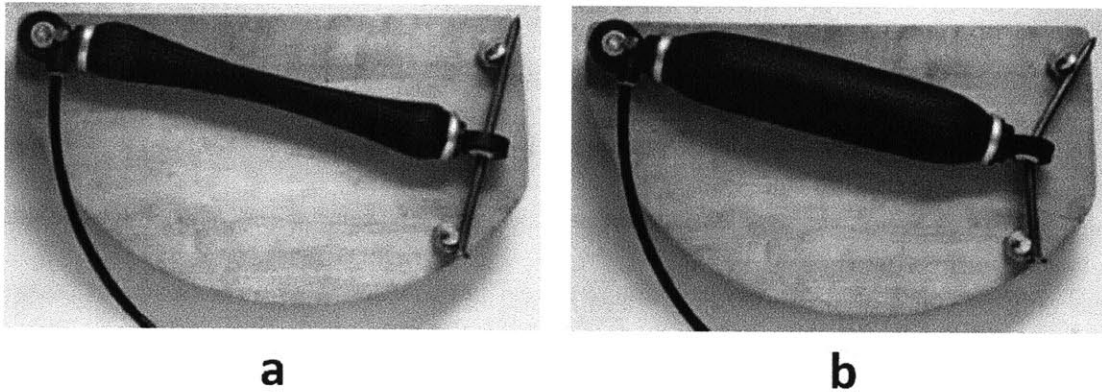


Figure 12: 30 mm diameter pneumatic artificial muscle developed by the Shadow Robot Company a) extended and b) contracted [41].

Though it has a high degree of potential dexterity owing to its mechanically intricate design, the Shadow Dexterous Hand demonstrates only limited realized dexterity. The Hand is capable of performing simple manipulation tasks such as picking up balls, turning a screwdriver, and opening a jar, but the procedures for executing these tasks are largely scripted. The positions of the Hand's components and the forces applied by its artificial muscles must all be pre-programmed, a cumbersome process for even simple operations. Though it is equipped with

the mechanical means to perform dexterous tasks at human speeds, in practice, the Shadow Dexterous Hand is constrained to performing tasks slowly due to its limited sensory capabilities. The Hand features only a rudimentary tactile sensory system and no closed-loop visual sensory system that would allow it to locate itself relative to objects in its immediate environment. The absence of these key features substantially limits the Shadow Dexterous Hand's ability to successfully emulate human dexterity.

3.4 The Ishikawa Manipulator and Function-Focused Design

Like the Shadow Dexterous Hand, many robotic arm and hand projects around the world have focused on the emulation of anthropomorphic form in an effort to match or exceed the human hand in terms of potential dexterity [1, 2, 11, 28]. However, due to the inevitable complexity of the resulting systems, the products of these projects have commonly demonstrated only limited realized dexterity. Other projects have taken a different approach, foregoing the constraints of the human form in favor of mechanical simplicity and emphasizing high realized dexterity in the design process as opposed to high potential dexterity. One of the most successful products of this approach is the high speed three-fingered manipulator developed by the Ishikawa Komuro Laboratory of the University of Tokyo. The Ishikawa manipulator couples a simple mechanical platform with intensive tactile and visual sensory systems to perform dynamic, highly dexterous tasks. It features a total of 8 degrees of freedom, two on each of its three fingers and two at the wrist, and weighs a total of 0.8 kg. Its finger joints are actuated by small harmonic drive gears and high-power mini-actuators contained within each finger link, which enable each joint to execute 180° flexions and extensions in approximately 0.1 s. Each the manipulator's three fingers are capable of a maximum force output of 28 N at their tips [22].

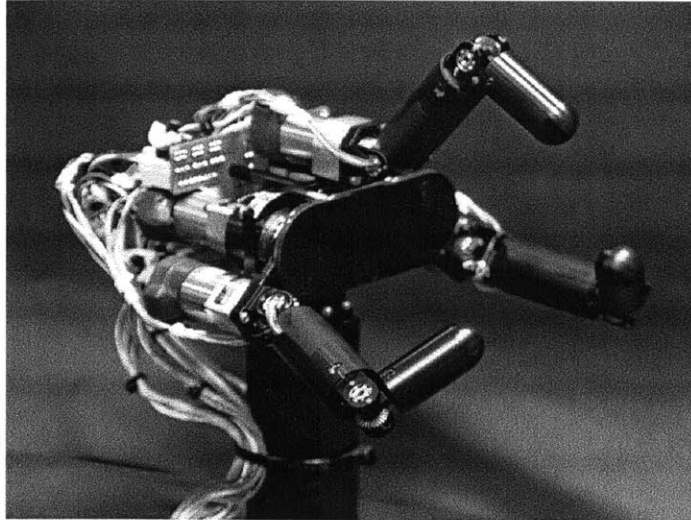


Figure 13: The high speed three-fingered manipulator developed by the Ishikawa Komuro Laboratory of the University of Tokyo [22].

Though the Ishikawa manipulator's mechanical system allows it to perform high speed transitions between numerous spatial configurations, it is the manipulator's visual and tactile sensory systems that direct these transitions and ultimately enable the successful execution of dexterous tasks. For visual information, the manipulator employs a massively parallel vision system known as a column-parallel high speed vision system. The system features a 128×128 photo detector array with a sampling rate of 1 kHz. Two of these systems are used by the manipulator simultaneously for three-dimensional targeting [22]. Tactile information is delivered to the manipulator through six high speed tactile sensor arrays positioned on the undersides of its finger links. These arrays, made from pressure-conductive rubber, weigh approximately 0.2 g/cm^2 and have a sampling rate of 1 kHz [24]. Together with its high speed mechanical platform, the Ishikawa manipulator's visual and tactile sensory systems enable it to perform a plethora of dynamic object manipulations – that is, manipulations of objects through statically unstable states. The manipulator is capable of catching spheres and cylinders,

dribbling a ball, spinning a pen, and tying a knot [22, 24, 45, 47]. All of these tasks are performed autonomously and repeatably, with the manipulator making use of its visual and tactile information sources to accommodate moderate physical discrepancies between task iterations.

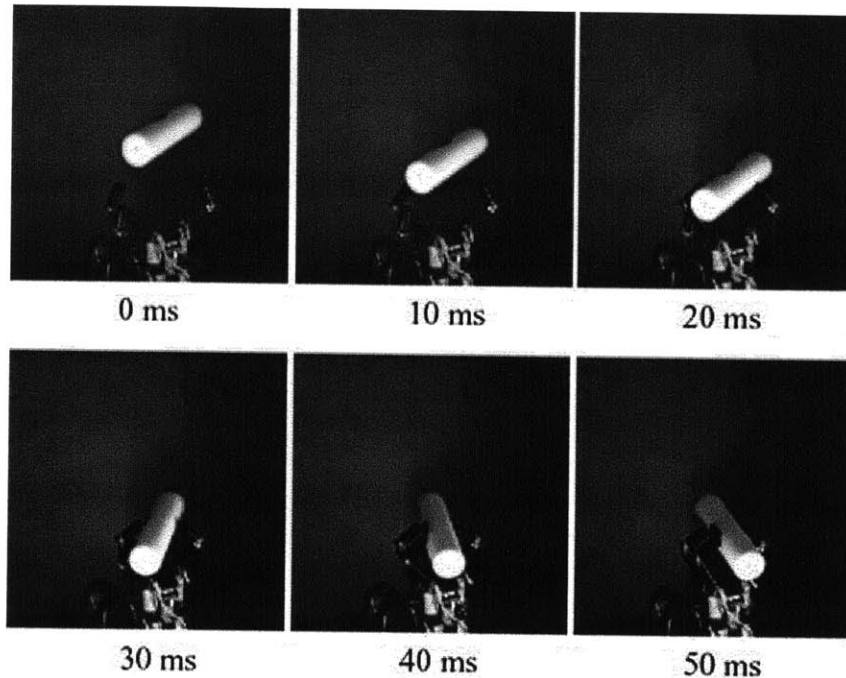


Figure 14: The Ishikawa manipulator catching a falling cylinder [22].

3.5 Future Prospects

Though undoubtedly dexterous, the Ishikawa manipulator is limited in its manipulation capabilities by its minimalistic kinematic structure. Though extending the manipulator's potential dexterity by adding another finger or including an additional joint in each of its existing fingers is a mechanically facile task, such additions would likely add significant complexities to the system's control architecture. It is not difficult then to see how mechanically intricate

anthropomorphic arm and hand projects such as the Shadow Dexterous Hand could exhibit such significant discrepancies between their potential and realized dexterities. Combining a mechanical platform as complex as the Shadow Dexterous Hand with visual and tactile sensory systems as intensive as those used by the Ishikawa manipulator poses significant engineering challenges indeed. It is likely that the integration of these two uniquely successful approaches to robotic arms and hands will be a defining characteristic of the next generation of humanoid robots.

Chapter 4

Conclusion

The present work has touched on only a small subset of the multitude of engineering challenges currently being addressed by researchers in the field of humanoid robotics. While the two key challenges faced by developers focused on emulating the human body have been reviewed, major challenges in the domain of artificial intelligence and machine learning, challenges essential to emulating the human brain, have not been examined. Many research groups around the world are actively addressing issues related to skill development and autonomy for humanoid robots, leveraging anthropomorphic robotic forms to generate anthropomorphic behavior [4, 5, 6]. Their approach is motivated by the observation that the human body is the only means by which the human brain derives information regarding the physical world. The human form is thus intimately tied to human intelligence and it is hoped that humanoid robots, which share a similar form, may be capable of developing a similar intelligence.

Human intelligence and self-awareness have given rise to a powerful desire for self-understanding. This desire is embodied in a drive for self-replication, the conception of artificial humanoid entities whose creation would ultimately demonstrate a mastery over the human form. Progress towards this goal is accelerating, spurred on by enabling advances in the fields of computer science, materials, and manufacturing. In the coming decades, humanoid robots will undoubtedly become more and more like their creators and, unlike any other product of human engineering, may slowly blur the line between how humans interact with their machines and how they interact with each other.

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