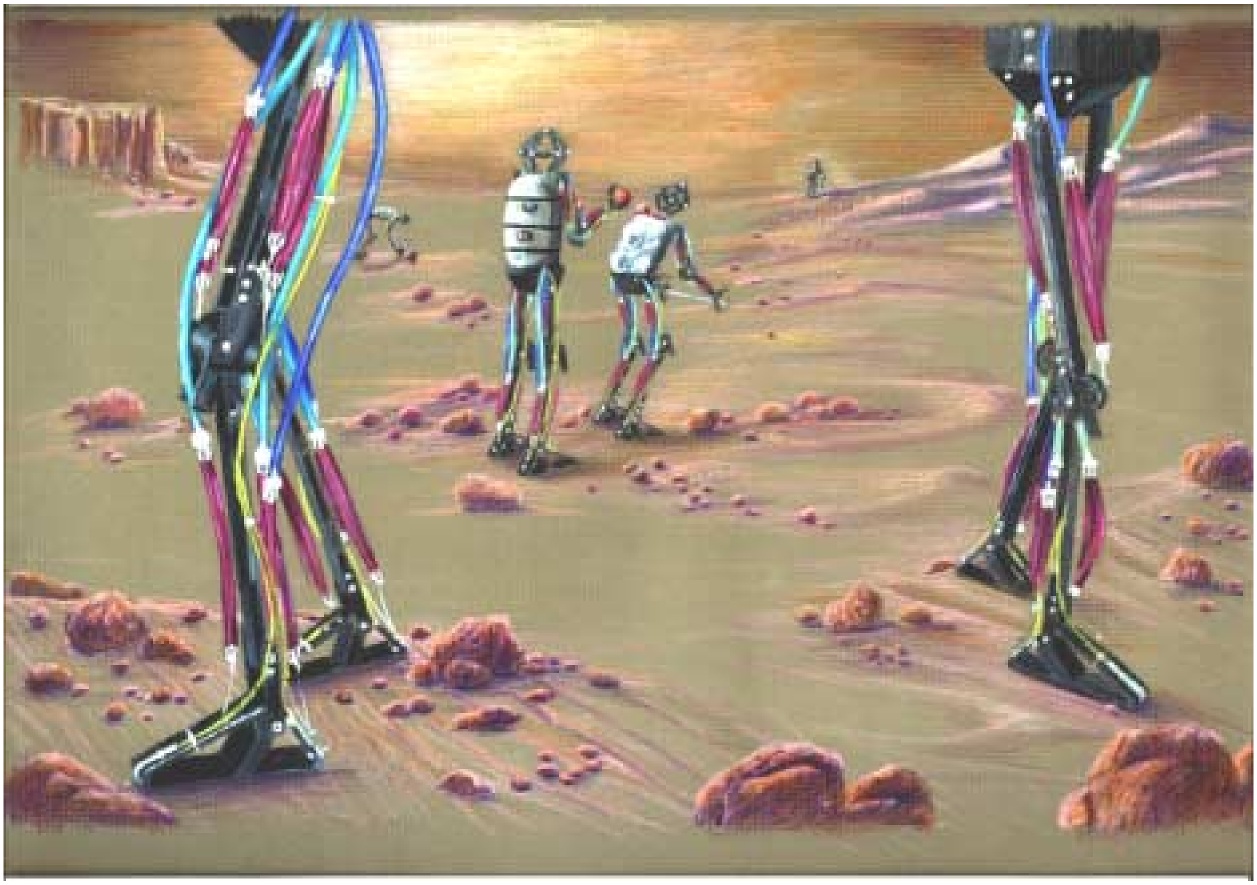
Biologically Inspired Legged Robots for Space Operations



Final Report NIAC Phase 1

(Adapted version for WWW publication)

NASA Institute for Advanced Concepts

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Important Notice

This public report is adapted from the complete and extensive final phase I report that has been submitted to NIAC. A patent is in preparation to protect the ideas and technology development described in this report. ECI and IIS Bio-Bot are registered trademarks of IIS Corp.

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Executive Summary

At IIS, we envision the creation of biologically inspired robots that will function in a community of intelligent agents. These robots will be able to traverse and operate over rough terrains and in difficult conditions in an autonomous fashion. Each robot will be a specialized agent with different performance levels.

The general objective of NIAC phase I was to develop a first prototype of biologically inspired robot, which is referred to as the IIS Bio-Bot. The Bio-Bot is a two-legged robot with 18 artificial muscles. The Bio-Bot employs anatomical and physiological constraints, such as force-length and force-velocity characteristics of muscles, and self-limiting joints, such as the knee. Muscles, either active or passive, provide “spring-like” properties. Both types of built-in constraints provide mechanical feedback that simplifies the control of a multi-joint system. Mobility and operation of the robot is based on the control of functional muscle groupings. This is a newly introduced concept that greatly simplifies control of multi-joint systems. These muscle groupings also provide the force and position control that is required in e.g. walking and grasping. The muscle groupings and built-in constraints are unique to biological systems.

The first prototype of the two-legged Bio-Bot demonstrated the power and future potential of the biologically inspired approach. Initial development in phase I focused on open loop control for standing and walking. Even in the absence of sensory feedback the Bio-Bot was capable of independent standing using open loop control, able to reject significant disturbances while in open loop control because of intrinsic actuator properties, and able to generate rhythmic walking in open loop mode by use of *if-then* rules obtained from knowledge of biological movements. It should be noted that this is very difficult to accomplish in conventional robotic designs. Conventional designs heavily depend on feedback. Further development of this two-legged Bio-Bot in phase I focused on further implementation of sensors for intelligent control of *if-then* rules (closed loop). At present, with only 2 force and 2 tilt sensors, the Bio-Bot is capable of standing and rhythmic walking using sensory feedback in close loop control. Control of standing in forward/backward and left/right plane uses seven *if-then* rules. Control of rhythmic walking uses only four *if-then* rules.

To our knowledge, our Bio-Bot is unique in the world. It demonstrates the power of biologically inspired robots in simplifying control compared to conventional engineering-based robot designs. The biologically inspired approach has great potentials toward the development of robots for space exploration and operation. Future work is directed toward the design and development of versatile robots capable of intelligent control, adaptive behavior, reasoning and cooperation in communities of agents.

1 Introduction

1.1 Biologically Inspired Robots

Imagine the possibilities that arise if we are able to develop robots based on the principles that enhance performance of biological systems. We foresee great potentials for the contribution of biologically inspired legged robots for space exploration and operation.

By developing biologically inspired robots that posses human-like features such as flexibility, versatility and intelligent behavior, robots used for space exploration can be trained both as autonomous explorers and as functional extensions of human senses and performance (tele-robotics). Missions dedicated to science and sample return can benefit from the use of biologically inspired robots in environments where human life cannot be sustained. Human direction can be safely and cost effectively provided via tele-communication with scientists and engineers on Earth or the closest space station.

1.2 What Do We Envision?

At IIS, we envision the creation of biologically inspired robots that will function in a community of intelligent agents. These robots, called IIS Bio-Bots, will be able to traverse over rough terrains and operate in difficult conditions as autonomous explorers. Each Bio-Bot will be a specialized agent with different specialties. For instance, in field studies some may be trained for (fragile) object manipulation or analysis, whereas others may be trained for problem solving to explore novel situations. Developing a Bio-Bot's specialized behavior is based on implementing knowledge from analysis and simulation as well as imitation learning of human behavior. Training is a natural process since the Bio-Bot resembles human functionality. We envision our Bio-Bots as cooperative and collaborative. They will interact and reason among themselves as well as with other robotic systems.

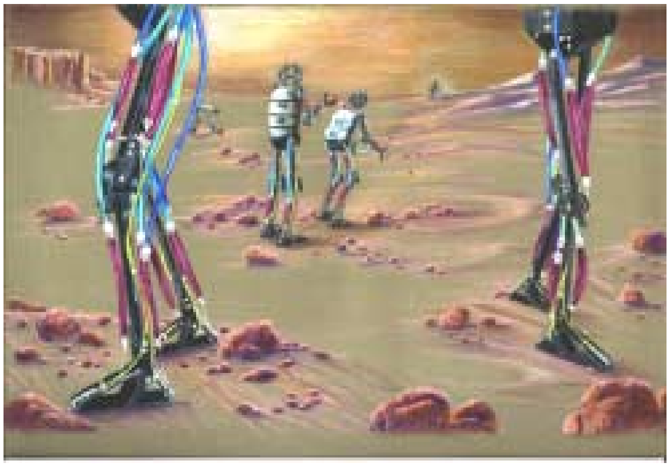


Figure 1. Biologically inspired robots at work.

The potential of the human-like features opens up new possibilities – Bio-Bots can be viewed as extensions of human senses and functions. Human direction can be safely and cost effectively provided via tele-communication with scientists and engineers on Earth or the closest space station. For instance, paleontologists or geologists can provide guidance and suggestions to the Bio-Bots on e.g. Mars regarding recognition and selection of interesting and exotic rocks or fossils. Likewise, they can interact with the Bio-Bots regarding the installation and maintenance of complex (scientific) instruments.

We envision the Bio-Bot to be an extension of our initial prototype of a two-legged robot toward a robot with four limbs: two legs and two arms. In this way, the Bio-Bot will contribute to the optimization of overall functionality and flexibility of legged systems by being a two-to-four legged robotic transformer. The Bio-Bot will be able to transform depending on task requirements and environment conditions. For instance, the use of four limbs is beneficial for climbing on rocks, whereas the use of only two legs is sufficient for level-ground walking in which case the arms can be used for object manipulation. Robustness and sustainability is provided by the use of multiple joints, legs and artificial muscles creating a built-in redundancy. In case of joint or muscle damage, the Bio-Bot will be able to adapt its functionality similar to how biological systems respond. For instance if an ankle muscle is injured, the Bio-Bot may “limp” but not loose the ability to walk.

1.3 Biologically Inspired Approach

We have developed a new way of thinking about robotic design. The biologically inspired approach does not follow the conventional line of engineering. In our approach, we take advantage of the control and design features that enhance performance in biological systems. Features that have been described since the pioneering work by, for instance, Leonardo da Vinci and Johannes Borelli. It is not our goal to duplicate the total complexity of these systems. That would not be possible. Instead, we take the knowledge from sensory and motor research in biological systems and implement that knowledge in the design of our biologically inspired robots. The biologically inspired approach provides for flexible and versatile robotic systems. It also provides a basis for intelligent control and behavior.

1.4 Phase I Objective

The general objective of phase I was to develop a first prototype of the IIS Bio-Bot. The purpose of this prototype is to:

- Demonstrate the use and implementation of artificial muscle actuators.
- Demonstrate the concept of functional muscle groupings for the control of standing and walking.
- Demonstrate the simplicity and power of intelligent control using the concept of functional muscle groupings and passive dynamics.
- Demonstrate standing and walking performance.
- Evaluate the advantages of biologically inspired approach.
- Determine the feasibility of the proposed concept.
- Describe the major technical issues for phase II.

In the next chapter, the performance and progress of the phase I work is reported in chronological order. The content is adapted from each individual monthly report as they have been submitted to NIAC at the end of every month.

2 Performance Phase I

2.1 Objectives – November 1998

- Design and manufacture hardware skeleton for IIS Bio-Bot
- Design and manufacture artificial muscle actuators
- Attach muscles to skeleton
- Determine functional muscle groupings for walking

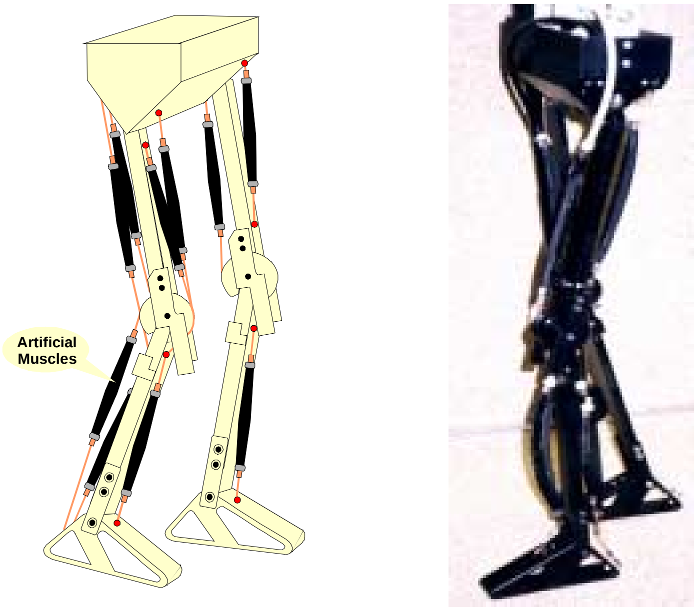


Figure 2*.* Schematic diagram (left) and first prototype (right) of IIS Bio-Bot.

2.1.1 Design and manufacture hardware skeleton for IIS Bio-Bot

A first prototype of IIS Bio-Bot has been designed and assembled. Technical diagrams of each of the parts were drawn by Dr. Jacobs and manufactured at a local hardware manufacturer. The Bio-Bot consists of 8 segments: 2 feet, 2 lower legs, 2 upper legs, a pelvis and trunk (Figure 2). Each body segment is made out of aluminum. The length of each body segment and the dimension of each joint have been scaled according to biomechanical models from humans. The IIS Bio-Bot's height is 90 cm.

2.2.2 Design and manufacture artificial muscle actuators

In November, the IIS Bio-Bot is supplied with 16 artificial air muscles, 8 for each leg (Figure 2). We constructed air muscles of different lengths and have successfully tested their strength, durability, and contractility. The air muscles consist of flexible tubing inside a braided sleeve. One end of the muscle is closed while the other end is open and connected to an air supply line. By supplying pressurized air the muscle shortens, generates force and applies torque at the joint(s) that it crosses. It has been experimentally shown that this combination of flexible tubing and braided sleeving closely resembles the dynamics of human muscles. Air muscles were used since they are currently the only type of artificial muscle that are strong and fast enough to generate the required force and speed for walking. Other artificial muscles (for instance muscle wire, electro- and chemical-polymers, etc.) are still only capable of producing forces in the order of a few grams, have slow activation dynamics (> 500ms), and/or remain in laboratory settings. We will keep ourselves up to date about the development and testing of electro-static polymers. These muscles are promising and once they have been fully tested in the lab, we anticipate implementing the polymers in our future design.

2.2.3 Attach muscles to hardware skeleton

In November, the muscles were attached to only one leg of the Bio-Bot. The positions of the origins and insertions were derived from biomechanical models developed by Dr. Jacobs. As can be seen in Figure 2, the muscles do not span the entire distance between origin and insertion, rather additional wire connected to the muscle acts as the tendon for each muscle-bone junction. At each segment, close to the joints, perpendicular pins were attached and can be adjusted to obtain realistic muscle moment arms at each joint. Dr. Jacobs developed models for realistic muscle moment arms that were scaled to the Bio-Bot’s size. The length of the air muscle determines the maximum force that can be delivered and the length range of the muscles. In November, we manufactured three different muscle lengths that were used for each individual muscle: i.e. muscles crossing one joint are longer than muscles crossing two joints. The selection of muscle length was guided by anatomical and biomechanical principles of human muscles. Muscles crossing only one joint tend to have longer fibers to control joint position. In contrast, muscles crossing two or more joints have shorter fibers to control force and movement direction. We started the process of a precise analysis of the passive and active range of motion of the muscles. It was our aim to resemble the range of muscle movement to be similar to human muscle movements. We concluded that the muscle movements in the IIS Bio-Bot have a very nice resemblance to human muscle movements.

2.2.4 Determine functional muscle groupings for walking

Our first attempt in defining functional muscle groupings was to divide the control of walking in the control of speed, height, and body (trunk) attitude. The performance variables were defined by the task requirements that determine the speed, height and attitude. The relationship between the functional muscle groupings and the action-related performance variables is shown in Table 1. Six functional muscle groupings were defined for both the stance and the swing phase for each leg. Each muscle grouping was a combination of different one-joint and two-joint muscles. Each leg consists of 8 muscles (5 one-joint and 3 two-joint muscles; Figure 2). The functional muscle groupings were derived from research on: (1) mechanical requirements for multi-joint control of muscles, (2) walking with specific attention to muscle coordination, and (3) physical legged (robotic) systems.

Table 1. Definition of control events for walking. The control of walking was defined in three parts that cover the stance and swing phase for each leg and the control of the upper body. The three controllers are: (1) speed control, (2) height control, and (3) body (trunk) control. For each controller, different control events were distinguished. For instance, the height controller has three phases: (1) loading event, (2) gliding event, and (3) a push-off event.

Controller	**Stance Phase Walking**			**Swing Phase Walking**		
I. Speed				Lift-off	Position	Prepare
II. height	Loading	Gliding	Push-off			
III. Body	Stabilize trunk					

2.2 Objectives – December 1999

- Develop hardware and software to control muscles
- Test individual muscles and functional muscle groupings
- Develop and test open loop control of the muscle groupings for walking

2.2.1 Develop hardware and software to control muscles

In the month of December, we established the interface between computer software, control card, solenoid valves and 18 muscles (Figure 3-5). A digital IO card connects to 18 miniature solenoid air valves. Using flow and pressure regulators, the force and speed of the muscle contraction was set. For the first prototype, we decided to control only the on/off times of muscle contraction using the IO card and leave the air pressure and flow constant.

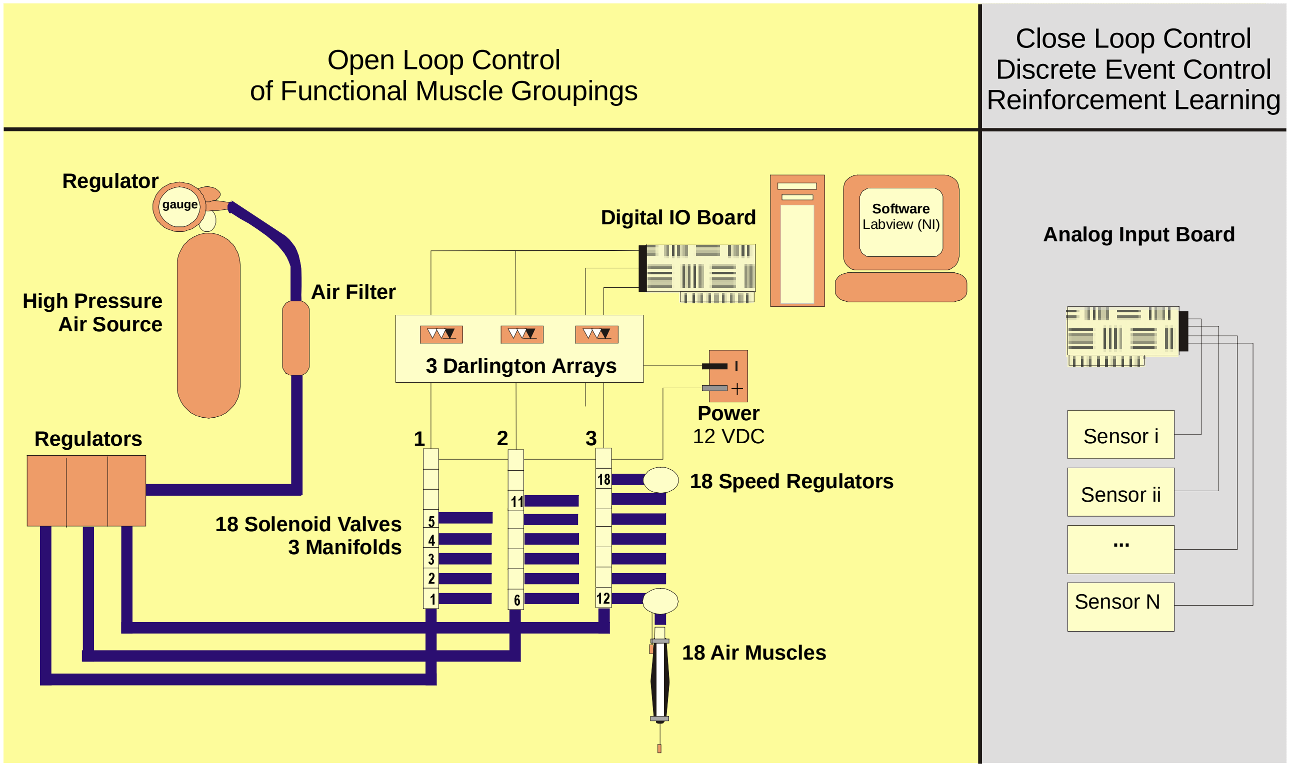
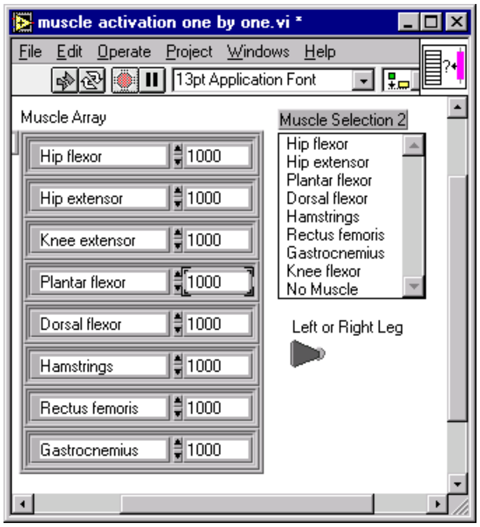


Figure 3. Schematic diagram representing the hardware and software interfacing. Initial work focused on establishing open loop control thereby allowing us to control the individual muscles and muscle groupings. We were able to successfully generate IIS Bio-Bot's first walking steps with it attached to a pushcart (Figure 6). The next task focuses on developing (fuzzy) discrete event control and reinforcement learning, which will be developed in the next 2-4 months.

2.2.2 Test individual muscles and functional muscle groupings

Programs controlling the IO card and thereby actuating the muscles were written in Labview (National Instruments Inc.). Using the Labview programs, we tested the active movement generated by individual muscle actions (Figure 4), actions of muscle groupings, and simultaneous actions of muscle groupings of the right and left leg. We have also developed a program in Labview that allows us to control the timing (coordination) of the different muscle groupings.



Muscle Array
Hip flexor 1000
Hip extensor 1000
Knee extensor 1000
Plantar flexor 1000
Dorsal flexor 1000
Hamstrings 1000
Rectus femoris 1000
Gastrocnemius 1000

Muscle Selection 2
Hip flexor
Hip extensor
Plantar flexor
Dorsal flexor
Hamstrings
Rectus femoris
Gastrocnemius
Knee flexor
No Muscle

Figure 4. An example of a Labview program written for the testing of individual muscles. This is the front panel in Labview. Behind this panel is the wire diagram that connects the muscle selections with the proper hardware configurations.

2.2.3 Develop and test open loop control of the muscle groupings for walking

We have established our first successful open loop control of walking (Figure 5 and 6). The IIS Bio-Bot made its first walking steps while it was attached to a pushcart (Figure 6). This was very exciting since this initial control is based on only a setting of air pressure and airflow and an initial trial of coordinating the timing of the walking cycle phases. These results indicated that the timing of the muscle groupings would be most crucial for the control of stable walking – which is in accordance to our initial ideas on the control of walking.

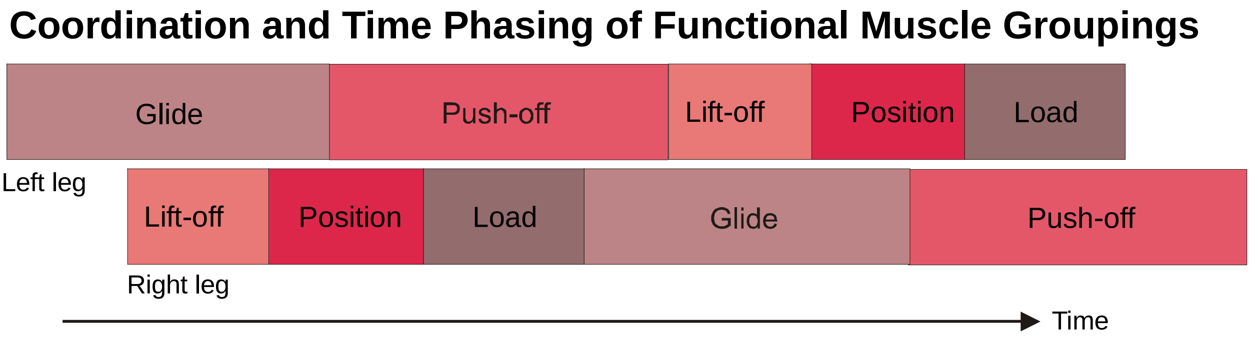


Figure 5. Schematic diagram representing a Labview program that controls the different muscle groupings for left and right leg. The length of each box represents the time and coordination of actuation of the muscle groupings for both legs. The following muscle groupings are defined: Glide, Push-off, Lift-off, Position and Load. Note that compared to Table 1, only 5 groupings were defined. It was concluded that the groupings *prepare* and *loading* could be condensed to one grouping called *load*. Different one-joint and/or two-joint muscles define each grouping. For instance, Lift-off includes the simultaneous action of the hip flexor, knee flexor and dorsal flexor muscles. Using this coordination pattern of the groupings we were able to generate IIS Bio-Bot's first walking steps.

(A) ***(B)*** ***(C)***

Figure 6. Prototype of the IIS Bio-Bot (December 1998). **A**. The Bio-Bot was attached to a push-cart to maintain stability during the learning phase. **B**. Side view of the muscles and the leg. **C**. Close up of the muscles around the knee joint.

2.3 Objectives – January 1999

- Demonstration of walking movements using the concept of functional muscle groupings
- Selection of sensors
- Report on legged robots

2.3.1 Open loop control

We successfully completed the first part of the project: i.e. the demonstration of controlling the functional muscle groupings for two-legged walking in an open loop control mode. In December, we established our first successful open loop control of walking using five and six muscle groupings per leg. In January, we further developed this open loop control and focused on the question of how many muscle groupings are required to successfully produce walking-like movements.

Coordination and Time Phasing of Functional Muscle Groupings

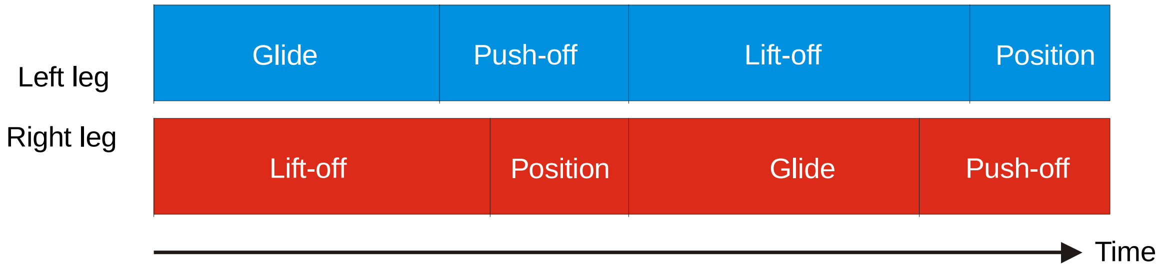


Figure 7. Open-loop control schema. Diagram representing the Labview program that controls the different muscle groupings for left and right leg. The length of each box represents the timing and coordination of actuation of the muscle groupings for both legs. The following muscle groupings are defined: Glide, Push-off, Lift-off, and Load. Different one-joint and/or two-joint muscles define each grouping. For instance, Lift-off includes the simultaneous action of the hip flexor, knee flexor and dorsal flexor muscles. Using this coordination pattern of groupings we were able to generate repetitive walking-like movements.

We have been able to bring down the total number of necessary muscle groupings from 6 to 4 per leg (Table 1 and Figure 7). Again, these results of open loop control indicate that the timing of the muscle groupings would be most crucial for the control of stable walking – which is in accordance to our initial ideas on the control of walking.

2.3.2 Selection of sensors

Another objective in December was to start selecting the sensors that will be attached to the IIS Bio-Bot. These sensors will be used as sensory feedback by the *if-then* (fuzzy) control rules. At this point, it was anticipated to implement the following sensors:

Artificial stretch / tendon organs at the joints. These sensors are 2 mm thin and can be ordered in any length from 2 cm and up. Each sensor can be thought of as a piece of elastic with electrical connections on each end. The more you stretch it the higher the resistance. Once the elastic is released the resistance returns back to normal. The sensor can be attached such that it will span a joint that needs to be measured. By measuring the change in resistance, the angulation of the joint can be calculated. The sensor does not affect the limb movement.

Pitch, roll and yaw measurement at the trunk level with a triaxial sets of accelerometers and magnetometers (MicroStrain Inc). Orthogonal arrays of magnetometers and accelerometers are used to compute the pitch, roll and yaw angles over a wide angular range. The sensor is a 3-axis orientation sensor capable of measuring: ± 180 degrees of yaw heading, ± 180 degrees of pitch, and ± 70 degrees of roll.

Force Sensitive Resistors (FSRs) for force/touch measurements at the feet (Interlink Inc.). FSR is a polymer thick film device, which exhibits a decrease in resistance with an increase in applied pressure to the active surface. FSR is not a load cell or a strain gauge, though they have very similar properties.

2.3.3 Report on legged robotics

Dr. Jacobs compiled an extensive literature study (omitted from report). This report discussed the nature of our biologically inspired approach. It also provided an overview of the work being conducted on different legged robots by MIT, Honda Inc., Delft University, Cornell University, etc.

2.4 Objectives – February 1999

- Independent standing
- Integration of force sensors in hardware

2.4.1 Independent standing

This month, we focused on the development of the control of standing and walking without the pushcart, i.e. to demonstrate dynamic and static stability. For that purpose, we changed the position of the valves so that they are now situated at the pelvis condensing the weight closer to the pelvis (Figure 8). Previously, all the valves were attached to the trunk about 20 cm higher than the pelvis. The IIS Bio-Bot is now completely detached from the pushcart and can be seen as a free-standing legged robot, except from the umbilical cord of wires that connects the computer and the hardware.


(A) (B) (C) (D)

Figure 8. The IIS Bio-Bot is now a free-standing legged robot (A is front view and B is side view). Static stability during standing was demonstrated by the pictures taken when the Bio-Bot was pushed sideways (C) or pushed forward (D). The Bio-Bot maintained standing as is illustrated by the fuzzy boundary around the Bio-Bot caused by a film exposure time of 3 seconds.

We have developed and successfully established control of open loop standing (Figure 8). The IIS Bio-Bot is able to stand using muscle activation of the hip extensor and knee extensor muscles. Including the hip flexor and/or the rectus femoris, a two-joint muscle, provided more stiffness at the joints. However, for regular standing these additional muscle activations were not necessary. The

IIS Bio-Bot is relatively stable; i.e. when we push the Bio-Bot sideways or forward, it remained standing (Figure 8). This is a significant accomplishment since we have not yet implemented sensors in the muscle control. The unique intrinsic properties of artificial muscles enable active muscle dynamics of the hip and knee extensor as well as passive muscle dynamics of the gastrocnemius, a two-joint muscle, to accomplish stable standing (see also Figure 10).

Also in February, we started working on developing the control of independent walking using the open loop control schema for the functional muscle groupings that we successfully established in January (Figure 7).

2.4.2 Integration of force sensors in hardware

As previously mentioned, efforts were made to select appropriate sensors for position and force measurements. We included Force Sensitive Resistors (FSRs) for force/touch measurements at the feet. Four FSRs were attached under the foot, i.e. one at the back and one at the front of the foot for each foot. FSRs are polymer thick film devices that exhibit a decrease in resistance with an increase in applied pressure to the active surface. FSRs are not load cells or strain gauges, though they have very similar properties. An appropriate electronic circuit has been designed and soldered on a circuit board. An analog input card (16 channels) has been selected and purchased. We have been experimenting with sensing foot contact and the use of the force sensors as triggers for walking cycle as well as in standing. Therefore, existing Labview programs that has been previously developed for the open loop control were modified and extended to include feedback control for standing and walking.

2.5 Objectives – March 1999

- NIAC annual meeting
- Independent open loop control of standing and walking
- Intelligent control
- Third IIS project meeting

2.5.1 NIAC annual meeting

A great part of the work done in March was to prepare for the NIAC annual meeting. For the purpose of the meeting, i.e. to present feasibility of our ideas and to illustrate our future directions for NASA, we developed:

- A video demonstrating the capabilities of the robot after four months in the project (see www.iiscorp.com).
- An artistic perspective of the project (Figure 9). We worked with a professional artist to portray our futuristic vision of the project.
- A power point presentation.
- A brochure of the project that was used as a handout at the NIAC annual meeting (Appendix 1).

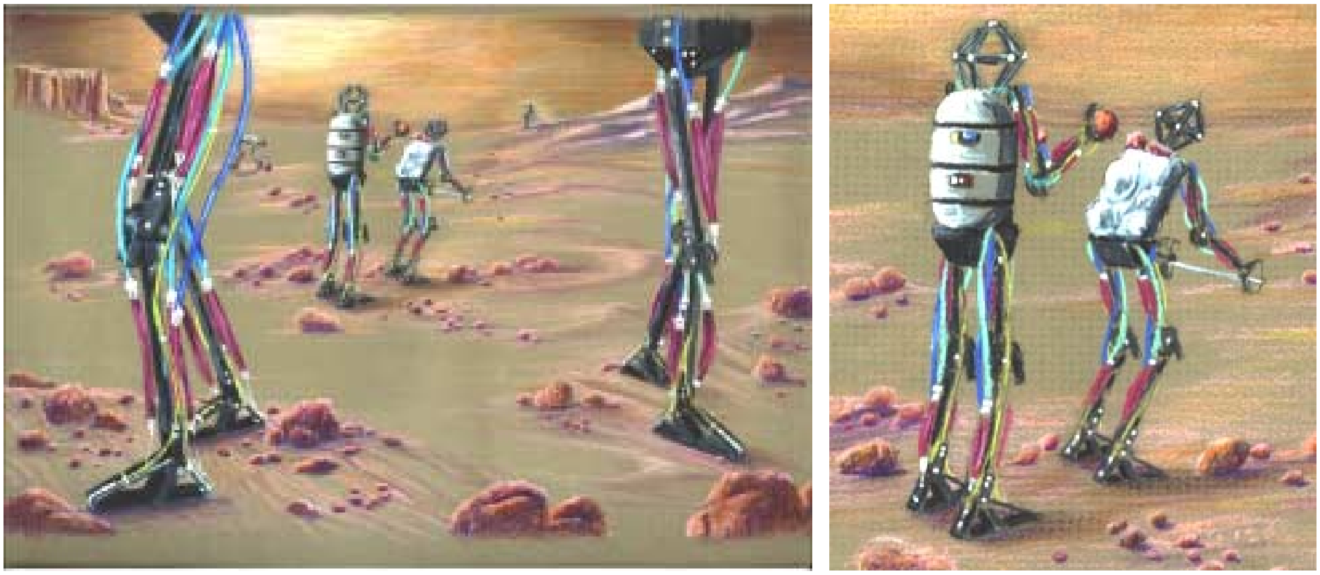
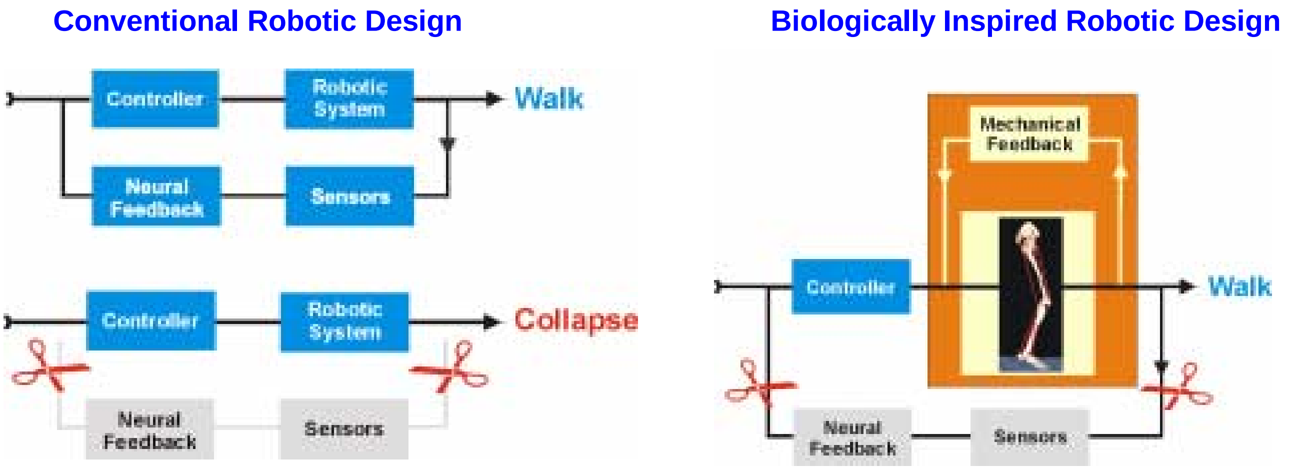


Figure 9. An artistic perspective of the project.

2.5.2 Independent open loop control of standing and walking

The power and future potential of the biologically inspired approach is demonstrated in our first prototype and documented in the video (www.iiscorp.com). With no sensors or neural feedback included yet, the robot is capable of independent standing and is able to reject significant disturbances while in open loop control because of intrinsic actuator properties. In addition, the use of simple *if-then* rules, obtained from knowledge of biological movements, generates rhythmic walking. To establish these abilities in a conventional engineering designed robot is difficult to accomplish (Figure 10). Conventional designed robots would already heavily depend on control to establish, for instance, stable standing. The ideas behind the simplification of the control in our biologically inspired robot are that it employs anatomical and physiological constraints, such as force-length and force-velocity characteristics of muscles, and self-limiting joints, such as the knee (Figure 10). Muscles, either active or passive provide "intelligent spring-like" properties. Both types of built-in constraints provide mechanical feedback that simplifies the control of a multi-joint system. Furthermore, the mobility and operation of the robot is based on the control of functional muscle groupings. These muscle groupings consist of different uniquely selected sets of muscles that provide the force and position control that is required in e.g. walking and grasping. These muscle groupings take advantage of the built-in constraints and thereby simplify control. This is unique to biological systems. Having established control for independent open-loop standing, the next task was to include sensors that provide neural feedback for the intelligent control of the robot.


Conventional Robotic Design

Biologically Inspired Robotic Design

Figure 10. LEFT: Conventional robotic design is heavily dependent on control. RIGHT: Biologically Inspired robotic design simplifies control by using mechanical feedback of muscles, tendons and joints.

2.5.3 Intelligent control

We started working on the ability to read sensor information data and to use the data in *if-then* rules to control the standing and walking. We have been able to successfully control individual muscles using the force sensor data from the feet while the robot was standing. So far, these *if-then* rules were programmed in Labview (National Instruments Inc). However, writing rules in Labview is not the most efficient way and does not provide us with the tools to develop the required intelligent control and reinforcement learning that we would like to have. To overcome these shortcomings of Labview, we started to work on the integration of ECI™ in Labview. ECI™ is the Environment for Computational Intelligence, a software package develop by our company that will be released by the end of this year. ECI™ allows us to write the intelligent control rules in a user-friendly environment. Our activities therefore focused on the development of the software interface (DLL file) that allows for the exchange of sensor information and control data between ECI™ and Labview. The next and final month of phase I focused on:

- Integrating ECI™ in Labview,
- Integrating additional sensors in the control of standing and walking, and
- Writing intelligent *if-then* control rules for standing and walking.

2.6 Objectives – April 1999

- Integration of ECI^{TM} in Labview
- Integration of additional sensors
- Intelligent control rules for standing and walking
- Reinforcement learning
- Hardware

2.6.1 Integration of ECI^{TM} and Labview

We have established the interface between Labview and ECI^{TM} (Environment for Computational Intelligence, IIS Corp). This interface was necessary so that we could overcome the shortcomings of Labview in writing *if-then* control rules and to provide an interface to include reinforcement learning. ECI^{TM} includes tools to develop *if-then* (fuzzy) rule basis, genetic algorithm optimization, and reinforcement learning modules. A DLL file was written which exchanges sensor and control information between Labview and ECI^{TM}. Now we are able to write the intelligent control rules in a user-friendly environment in ECI^{TM} and apply these to the muscles in the robot using Labview.

2.6.2 Integration of sensors

Two analog dual axis tilt sensors have been purchased and integrated into the robot. The sensors were attached to the lateral side of each upper leg and measure the tilt angle in sagittal (forward/backward) plane and frontal (left/right) plane with respect to the gravitational vector. The sensors have been integrated onto the electronic circuit board at the trunk and connected to the AD converter. In total, the AD converter acquires signals from eight sensors: per leg we have two force sensors under the foot, tilt angle in sagittal and frontal plane at the thigh. The signal from the two force sensors of each foot was combined to one signal in software.

2.6.3 Intelligent control rules for standing and walking

ECI^{TM} has been used to write intelligent *if-then* control rules for standing and walking. The type of control is called discrete event control. In ECI^{TM} labels define the sensory states (inputs) and control decisions (outputs). Connecting appropriate labels in input and output space creates the *if-then* rules. For the control of standing, seven *if-then* rules have been created. For the control of rhythmic walking only four *if-then* rules have been created. In the walking rules, the idea of passive walking was incorporated. For instance, if an action has been taken, passive dynamics will bring the robot to the next state at which point the next action will be taken (Figure 11). With this controller, we take advantage of the passive dynamics, which simplifies control as well as provides for efficient walking.

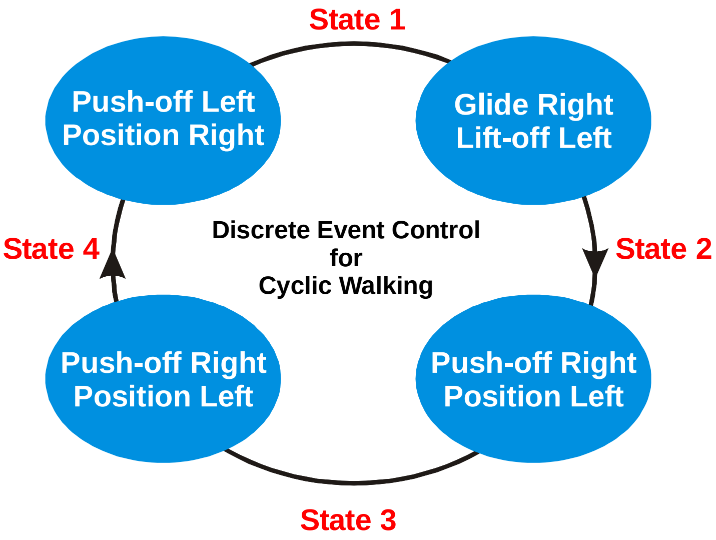


Figure 11. Graphical representation of the discrete event controller as defined for walking. Four unique *if-then* rules describe the control of cyclic walking using the concept of functional muscle groupings (i.e. muscle grouping glide, push-off, lift-off, position as defined for left and right leg). An example of a rule is: IF state 1 (i.e. sensor 1 is X and sensor 2 is Y), THEN activate muscle groupings Glide of the right leg and Lift-off of the left leg. The IF part of the rule is described outside the curve, between the ovals, and the THEN part is described in the ovals.

2.6.4 Reinforcement learning

We started to explore the use of reinforcement learning to tune the *if-then* rule base controller for walking. With reinforcement learning, the *if-then* rules would be tuned to the values of the labels in such a way that a desired performance is optimized. In setting up reinforcement learning one has to decide which label(s) is/are most appropriate to tune and which influence the performance of the controller the most. In addition, the performance has to be defined in terms of what is good and what is bad. A theoretical analysis has been done for tuning the state value that triggers push-off to optimize the performance in terms of walking height. Good performance is defined as small variation in walking height, whereas bad behavior is defined as a variation exceeding the boundary that is defined as small. Reinforcement learning will search for the state value that produces small variations and thus good performance. Once the rule base controller as defined in Figure 11 has been fully tested, we will implement the reinforcement learning strategy in ECI^{TM} and apply it to the Bio-Bot.

2.6.4 Hardware

An important requirement for walking is that the Bio-Bot can stand on one leg and smoothly transfer weight from one leg to the other (Figure 12, right). In order to fulfill that requirement we made some changes to the hardware. First, we replaced the single axis hip joint with a three-dimensional ball joint. A 3-D hip joint was required to provide smooth transitions from left to right leg and vice versa. Since an unconstrained 3-D hip joint allows excessive movements in the frontal plane (side-to-side leg movement) and in the horizontal plane (leg rotation), we added springs to reduce the degree of these movements to a more natural (human-like) range of motion (Figure 12). The springs are purely experimental and will soon be replaced by appropriate muscles. These muscles will provide abduction and adduction movement and are identified in the human body as m. tensor fascia latea and m. adductor longus and brevis. Second, we added a wooden piece at the lateral side and under the bottom of the foot to provide a convex structure. This convex structure provides a smooth rolling motion from side-to-side during walking.

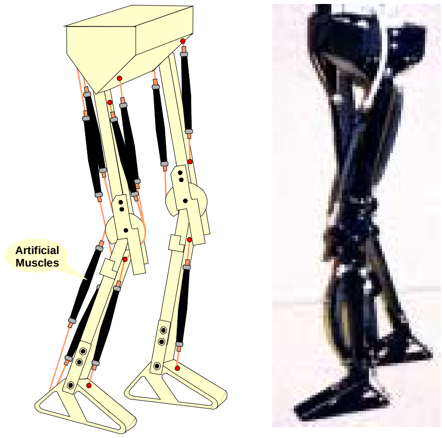
Figure 12. Prototype of the biologically inspired legged IIS Bio-Bot (April 1999). Sensors were attached to each thigh. A three dimensional hip joint was added to provide smooth transitions from one leg to the other during walking. Springs (to be replaced by muscles) were added to constrain the excessive movement of the new 3-D hip joint. A new foot design was added to provide smooth rolling motion during walking. In the right picture the robot is standing on <u>one leg</u>, i.e. the right leg.

2.7 Summary Phase I work

2.7.1 Objectives and deliverables for each month

Period	Tasks	Deliverable
November	• Design and manufacture hardware skeleton for IIS Bio-Bot • Design and manufacture artificial muscles actuators • Attach muscles to hardware skeleton • Determine functional muscle groupings for walking	• Hardware of IIS Bio-Bot • Drawings of IIS Bio-Bot • Picture of IIS Bio-Bot • Monthly report to NIAC
December	• Develop hardware to control the muscles • Test individual muscles and functional muscle groupings • Develop and test open loop control of the muscle groupings for walking • First meeting of project team (12/7/98)	• Open loop control walking-like movements of over-ground walking attached to push-cart • Pictures of IIS Bio-Bot • Monthly report to NIAC
January	• Open loop control of walking. • Start search for appropriate sensors to be included in *if-then* control. • Report on legged robots (Appendix 2) • Second meeting of project team (1/25/99): define technical issues to be addressed in Phase II	• Successful open loop control of walking-like movements using push-cart • Video of first walking steps • Monthly report to NIAC
February	• Development of control for independent standing • Start integration of force sensors in hardware	• Independent standing without push-cart • Pictures of IIS Bio-Bot • Monthly report to NIAC
March	• Independent open loop control of standing and walking. • Start developing intelligent control • Third meeting of project team (3/15/99): continue discussion on technical issues to be addressed in Phase II. Preparation of talk for NIAC Annual meeting • Preparation and attendance Annual NIAC meeting, Washington DC, March 24-26.	• Video showing stable standing and walking with (independent) open loop control (www.iiscorp.com) • Professional drawing of future ideas of project • Brochure of project (Appendix 1) • Presentation at NIAC annual meeting • Monthly report to NIAC
April	• Integration of ECI and Labview • Integration of sensors • Intelligent control rules for standing and walking • Start of developing reinforcement learning strategies for adaptation and tuning of muscle-driven movements • Hardware changes • Fourth meeting of project team (4/30/99): evaluation of NIAC phase I and concluding the focus for NIAC phase II	• Intelligent control using if-the rules for reasoning with multiple sensor information to control the functional muscle groupings for standing and walking • Development of reinforcement learning methods to tune the if-then rules aimed at independent and stable walking • Pictures of IIS Bio-Bot • Monthly report to NIAC

2.7.2 Picture gallery



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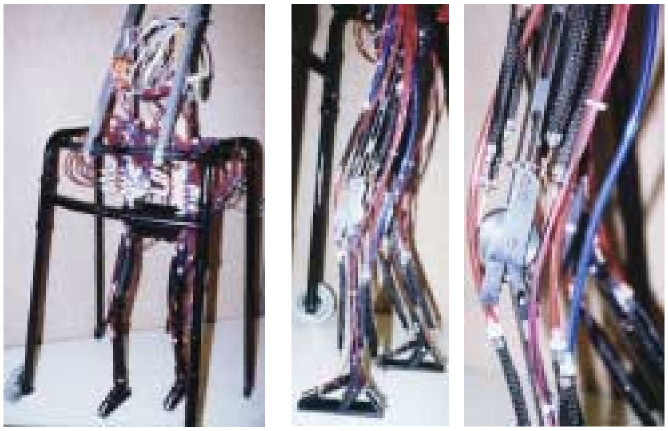

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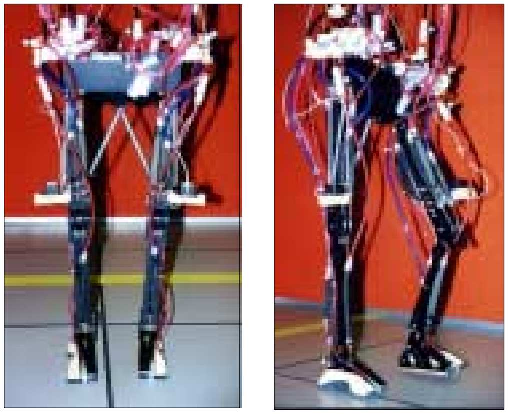
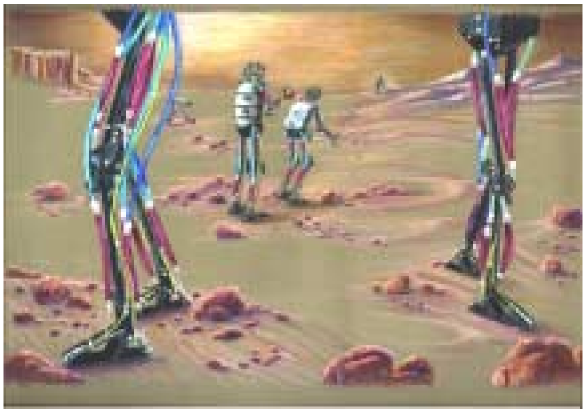


April 1999



Futuristic vision

3. Feasibility and Technical Issues

The general objective of phase I was to develop a first prototype of biologically inspired robot. The purpose of this prototype was to:

- Demonstrate the use and implementation of artificial muscle actuators.
- Demonstrate the concept of functional muscle groupings for the control of standing and walking.
- Demonstrate the simplicity and power of intelligent control using the concept of functional muscle groupings and passive dynamics.
- Demonstrate standing and walking performance.
- Determine the feasibility of the proposed concept.
- Describe the major technical issues for phase-II.

3.1 Technological feasibility – First prototype

We have developed our first prototype of the biologically inspired robot. After just 3 months in the project, we completed the designed of a legged robot with 18 artificial muscles. The robot employs anatomical and physiological constraints, such as force-length and force-velocity characteristics of muscles, and self-limiting joints, such as the knee. Muscles, either active or passive, provide “spring-like” properties. Both types of built-in constraints provide mechanical feedback that simplifies the control of a multi-joint system. Mobility and operation of the robot is based on the control of functional muscle groupings. This is a newly introduced concept that greatly simplifies control of multi-joint systems. These muscle groupings also provide the force and position control that is required in e.g. walking and grasping. The muscle groupings and built-in constraints are unique to biological systems.

The first prototype of the two-legged Bio-Bot demonstrated the power and future potential of the biologically inspired approach. Initial development (February and March) focused on open loop control for standing and walking.

Even in the absence of sensory feedback the Bio-Bot was:

- Capable of independent standing using open loop control,
- Able to reject significant disturbances while in open loop control, because of intrinsic actuator properties, and
- Able to generate rhythmic walking in open loop mode, by use of *if-then* rules obtained from knowledge of biological movements.

It should be noted that this is very difficult to accomplish in conventional robotic designs. Conventional designs heavily depend on feedback. Further development of this two-legged Bio-Bot (March and April) focused on further implementation of sensors for intelligent control of *if-then* rules. At present, with only 2 force and 2 tilt sensors, the Bio-Bot is capable of standing and rhythmic walking using sensory feedback in close loop control:

- Control of standing in forward/backward and left/right plane using seven *if-then* rules.
- Control of rhythmic walking using only four *if-then* rules.

3.2 State of the art: Concepts introduced

We defined a unique approach utilizing the principles that enhance the performance of biological systems. In our approach, the advantages of passive dynamics and neuro-physiological dynamics of biological systems were both employed. In summary, the following concepts were introduced:

- Use of anatomical constraints similar to and scaled to passive range of motion in human and animal joints.
- Use of artificial muscles or muscle-like actuators, instead of the torque generating motors, to provide efficient and more natural control.
- Use of one joint and two joint muscles to solve the problem of position and force requirements for control of multi-joint systems.
- Use of mechanical feedback that simplifies control (open and closed loop) of a multi-joint system based on built-in constraints such as muscles, tendons, and joints.
- Use of biomechanical and motor control data of walking to derive functional muscle groupings.

- Use of functional muscle groupings to simplify the control of complex tasks by defining muscle movements that move in tandem with each other. The groupings provide the required force and position control for walking.
- Use of simultaneous activation of one and two joint muscles to provide stiffness control without the loss of energy that occurs with activation of two opposing one-joint muscles.
- Use of performance related control, rather than individual joint control, to simplify the control computation algorithms.
- Use of simple *if-then* (fuzzy) rules to develop discrete event control for standing and walking. This way of control also enables a natural use of the experimental data.
- Use of simple *if-then* (fuzzy) rules to integrate the benefits of neural oscillator dynamics and passive dynamics. This way of control results in a very efficient and simple way of controlling walking.
- Use of reinforcement learning to adjust the timing of the functional muscle groupings and thereby further optimize the alternation between swing and stance legs to generate efficient and stable walking.

3.3 Benefits of biologically inspired approach

By developing biologically inspired robots that posses human-like features such as flexibility, versatility and intelligent behavior, robots used for space exploration can be trained both as autonomous explorers and as functional extensions of human senses and performance (tele-robotics). Missions dedicated to science and sample return can benefit from the use of biologically inspired robots in environments where human life cannot be sustained. Human direction can be safely and cost effectively provided via tele-communication with scientists and engineers on Earth or the closest space station. In addition, there is a strong need for legged systems that can travel and operate in difficult terrains, where existing wheeled vehicles cannot go. This is especially true for future missions to, for example, MARS where the planet surface is rugged and uneven. With the NIAC phase I work, we have demonstrated that this biologically inspired approach has great potentials for developing a new age of legged robots that:

- Allow for intelligent control in a flexible yet stable system.
- Facilitate travel and operation in rough terrains and difficult conditions.
- Facilitates high functionality and versatility in a low-mass system.

More specifically, the NASA benefits can be summarized as follows:

- **The Bio-Bot will provide for a flexible and versatile robotic system capable of:**
    - Travel over rough terrains and operate in difficult conditions.
    - A high degree of adaptation to optimize movement and behavior in a changing and dynamic environment.
    - Robustness and sustainability due to multiple joints and muscles in the legs.
    - Intelligent biologically inspired control.
- **The collection of Bio-Bots will provide for community of intelligent agents capable of:**
    - Interaction and cooperation within the community similar to teamwork in biological systems.
    - Tele-robotic interactions employing the functional extensions of human senses and performance.
    - Exploration in novel situations and environments employing human-like exploration.

3.4 Specific technical questions

When legged robots are introduced one can ask the question: **why use legs?** Articulated legs allow for an integrated sensory motor system that provides the following advantages:

- The control of such multi-joint legged systems can be inspired from how biological (animal and human) systems control movements. This way we can integrate nature's efficient solutions for controlling complex movements.
- In case of articulated legs one can include anatomical constraints such as a knee joint that cannot hyperextend, or an ankle and hip joint that are restricted in their range of motion. This provides additional constraints to the mechanical system and makes the control simpler by utilizing mechanical feedback.
- Articulated legs provide an increased range of mobility. This is important when a legged robot explores uneven terrain and needs to avoid obstacles.
- The use of legged systems provide active suspension that de-couples the path of the body from the paths of the feet. This results in smooth and efficient travel despite variations in terrain.
- In case of multiple joints, a legged robot is not dependent on one joint or one actuator. For instance, if one joint becomes impaired, other joints can take over. A legged robot won't

loose its complete functionality due to redundancy in the number of joints.

- Likewise, depending on task requirements and environmental conditions, a legged robot such as the Bio-Bot with four legs (two arms and two legs) will be able to transform between two- and four-legged locomotion.

There is a tradeoff between the number of legs and the overall functionality and flexibility of the legged robot. In our future design (Phase II), we have chosen to extend our prototype to four limbs: two legs and two arms. The idea is to have a two-to-four legged transformer, which reconfigures depending on the task requirements and environment conditions. For instance, the use of four limbs is beneficial for climbing on rocks, whereas the use of only two legs is sufficient for walking.

A similar question can be raised about **why use muscles as actuators?** Currently, there is strong development in the field of artificial muscles. This indicates that there is a need for biological systems/actuators. At this time, there are only a few labs using artificial muscles in their robotic design, however, artificial muscles will soon be common actuators in robotics. Muscle actuators provide the following advantages:

- Muscle actuators have their own passive and active dynamical characteristics, which limit the full range of possible joint movements. Limitation of joint movements greatly simplifies the control and introduces the concept of (active and passive) mechanical feedback. This is in sharp contrast to torque motors that need to be controlled at each possible angle.
- The use of artificial muscles creates a built-in redundancy and robustness that allows for self-repair and sustainability. The Bio-Bots will be able to adapt to injury similar to how other biological systems adapt. For instance, if an ankle muscle is injured, the Bio-Bot may “limp” but not loose the ability to walk.
- Muscles provide a system with multiple actuators. Artificial muscles are lightweight, low cost and provide efficient and natural movements. For the first prototype of the IIS Bio-Bot, air muscles were used since they are currently the only type of artificial muscle that is strong and fast enough to generate the required force and speed for walking. Other artificial muscles (i.e. muscle wire, electro- and chemical-polymers, etc.) are still only capable of producing forces in the order of a few grams, have slow activation dynamics (>

500ms), and/or remain in laboratory settings. In future, we anticipate to use of electric-control artificial muscles (such as electrostatic polymers) instead of pneumatic muscles. However, these muscles are still being tested and further developed. One of the problems is the requirement of high voltage for making the polymer sheets bend.

3.5 Design and development issues

The approach has great potentials toward the development of robots for space exploration and operation. Future work is directed toward the design and development of versatile robots capable of intelligent control, reasoning and cooperation in communities of agents. The completion of the design and technology development is projected over a time frame of 10 years. It is directed toward the development of a biologically inspired robot as an intelligent agent for space operations. Our multi-disciplinary project team will focus on:

- ***Component issues***
  - Artificial muscles (including performance, power and space suitability)
  - Sensors (including reliability, power and space suitability)
  - Self-contained power (including source and life time)
- ***Intelligent control issues: Mobility and operation***
  - Travel over even and rough terrains (including vision and navigation systems)
  - Maneuverability
  - Object manipulation (including touch, feeling and recognition)
- ***Intelligent behavior issues***
  - Autonomous nature
  - Transformation and versatility
  - Interaction and reasoning in different environments
  - Problem solving and reasoning
  - Task specialization of robots
- ***Intelligent agent issues***
  - Interaction and reasoning with other robotic systems
  - Interaction and reasoning with remote scientists (including communication time delays)
  - Cooperation and problem solving

3.6 Objectives NIAC Phase II

The primary objective of NIAC phase II is to address and (further) develop the concepts and technical issues that were introduced in phase I. More specifically, our multi-disciplinary project team will focus on:

- Development of **intelligent (movement) control** to enhance the functionality of the Bio-Bot. This includes the development of the Bio-Bot as a four legged robot (arms and legs).
- Integration of **intelligent behavior** to promote on-line learning and adaptation to different task requirements and environmental conditions. This includes developing the Bio-Bot as a two-to-four legged transformer.
- Development of strategies for **intelligent interaction and reasoning**. This will include the start of developing the Bio-Bot as an autonomous explorer and thus as an intelligent agent.

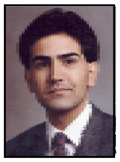
4. Project team & project meetings

4.1 Project team

For NIAC phase I, we developed a multi-disciplinary team of experts to develop the ideas of the biologically inspired robot. The IIS project team consists of:

Dr. Ron Jacobs, IIS Corp.

Principal Investigator, Bio-Mechatronics



Dr. Hamid Berenji, IIS Corp.

Computational Intelligence

Dr. Sujit Saraf, IIS Corp.

Control Engineering and Soft Computing

Prof. Robert Full, UC Berkeley

Integrative Biology (Consultant/Collaborator)

Prof. Felix Zajac, Stanford University

Biomechanical Engineering (Consultant/Collaborator)

4.2 Project meetings

In total four IIS project meetings were held which lasted for two hours. At each meeting the entire team was present. The meetings focused on the following aspects:

- During our first project meeting (12/7/98) we discussed:
  - ➢ Current status of the project by presenting the first prototype of the Bio-Bot;
  - ➢ Initiated our first discussion on the important technical issues and questions for Phase II that need to be addressed. A list of issues and questions had been generated and we planned to specifically address those during our next meeting in January (1/25/99).

- During our second project meeting (1/25/99) we discussed:
  - The current status of the project by presenting the progress of the Bio-Bot.
  - Our project in relation to other research in designing and controlling legged robots (e.g. at MIT Leg Lab, Honda Inc., Cornell University, etc.).
  - A report that addressed the technical Phase II questions generated during our first meeting.

- During our third project meeting (3/15/99) we discussed:
  - The current status of the project by presenting the progress of the Bio-Bot.
  - The content of the presentation for the NIAC annual meeting.
  - The technical issues and questions for Phase II.

- During our fourth project meeting (4/30/99) we discussed:
  - The current status of the project by presenting the progress of the Bio-Bot.
  - The work done in Phase I.
  - The direction and focus for Phase II.

Appendix 1 – Brochure describing project

Please refer to next two pages

About Intelligent Inference Systems (IIS) Corp.

IIS Corp.

Established in 1993 and located in the heart of Silicon Valley, Intelligent Inference Systems Corporation (IIS) is a frontier in providing key intelligent systems technology to businesses, manufacturers and the government. IIS is committed to integrating cutting-edge science and technology for developing future intelligent systems.

Research and Development

IIS is currently active in performing research and development in the following areas:

- Intelligent Systems and Control
- Neuro-Fuzzy Control
- Reinforcement Learning
- Multi-Agent Planning and Control
- Genetic Algorithms / Evolutionary Programming
- Biologically-Inspired Legged Robots

Courses and Training

IIS offers courses focusing on all major Computational Intelligence and Soft Computing technologies including Neural Networks, Fuzzy Logic and Genetic Algorithms. For schedules of current course offerings, please visit our web site at www.iiscorp.com.

Software Products

IIS develops either generic or custom-made software tools for Intelligent Control Systems, Computational Intelligence and Soft Computing (fuzzy logic and genetic algorithms). Application areas include Control Engineering, Automobile Manufacturing, Aerospace Engineering, Internet and BioInformatics.

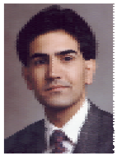
Consulting

Using cutting-edge technologies, IIS develops innovative solutions to meet clients' needs. IIS provides consulting to clients interested in developing intelligent systems in a wide range of applications and R&D oriented works, including for instance Aerospace Engineering, Automobile Manufacturing and Insurance Industry.

IIS Corp. is a Frontier in the Art and Science of:
Multi-Agent Planning and Control
Computational Intelligence
Intelligent Systems
Soft Computing
BioMechatronics
Robotics

Project Team

Dr. Ron Jacobs, IIS Corp.
PI, NIAC Research Fellow



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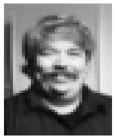
Computational Intelligence

Dr. Sujit Saraf, IIS Corp.
Control Engineering



Prof. Robert Full, UC Berkeley
Integrative Biology

Prof. Felix Zajac, Stanford University
Biomechanical Engineering

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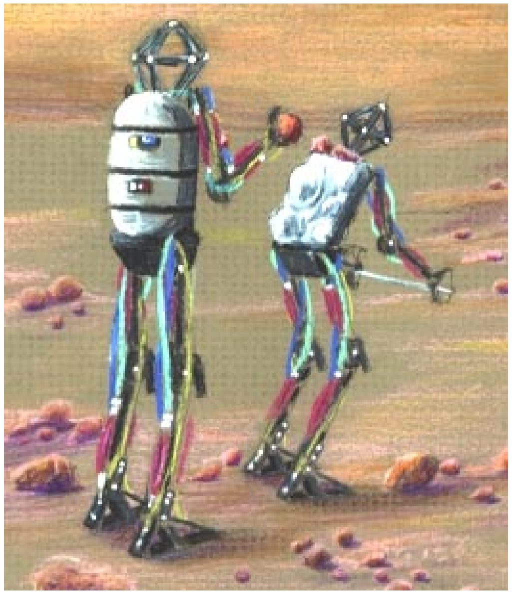
Intelligent Inference Systems Corp.
IIS CORP

Biologically-Inspired Legged Robots for Space Operations



A NIAC Supported Research Project

NIAC
NASA Institute for Advanced Concepts

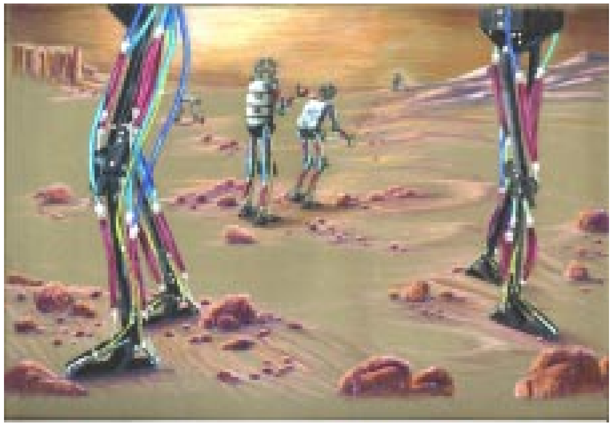
Biologically-Inspired Robots

Imagine the possibilities that arise if we are able to develop robots based on the principles that enhance performance of biological systems. We imagine great potential for the contribution of biologically-inspired robots for space exploration and operation.

Biological systems are unique in the way they move and are able to adapt to different environments. Their jointed limbs make them highly flexible and versatile, able to produce subtle and huge forces dependent on task requirements. Their adaptability emerges from the ability to interact with the environment and each other.

What do we envision?

We envision the creation of biologically-inspired robots that will function in a community of intelligent agents. These robots will be able to traverse and operate over rough terrains and in difficult conditions in an autonomous fashion. Each robot will be a specialized agent with different performance levels. For instance, some may be trained to be good at fragile object manipulation, whereas others may be trained to be good at problem solving to explore novel situations. We envision our biologically-inspired robots as cooperative and collaborative. They will interact and reason among themselves as well as with remote scientists or astronauts. The potential of the human-like nature opens up new possibilities – biologically-inspired robots can be viewed as extensions of human senses and functions. For instance, paleontologists or geologists can do work on Mars, or even on planets beyond the solar system, from their offices on Earth. In particular, this potential extension of human senses and functions will be ideal for exploration beyond the solar system where humans cannot go.



Biologically-inspired robots at work

Biologically-Inspired Approach

We have developed a new way of thinking about robotic design. The biologically-inspired approach does not follow the conventional line of engineering. In our approach, we take advantage of the control features that enhance performance in biological systems. Features that have been described since the pioneering work by, for instance, Leonardo da Vinci and Johannes Borelli. It is not our goal to duplicate the total complexity of these systems. That would not be possible. Instead, we take the knowledge from sensory and motor research in biological systems and implement that knowledge in the design of our biologically-inspired robots.

Technological Feasibility – First Prototype

Starting with a NIAC phase-I Award in November 1998, we have developed our first prototype of the biologically-inspired robot. After just 4 months in the project, we have designed a legged robot with 18 artificial muscles. The robot employs anatomical and physiological constraints, such as force-length and force-velocity characteristics of muscles, and self-limiting joints, such as the knee. Muscles, either active or passive, provide “spring-like” properties. Both types of built-in constraints provide mechanical feedback that simplifies the control of a multi-joint system. Mobility and operation of the robot is based on the control of functional muscle groupings. These muscle groupings provide the force and position control that is required in e.g. walking and grasping. The muscle groupings and built-in constraints are unique to biological systems.

The power and future potential of the biologically-inspired approach is demonstrated in our first prototype. With no sensors or neural feedback included yet, the robot is capable of independent standing and is able to reject significant disturbances while in open loop control. In addition, the use of simple if-then rules, obtained from knowledge of biological movements, generates rhythmic walking.

To our knowledge, our robot is unique in the world. It demonstrates the power of biologically-inspired robots in simplifying control compared to conventional engineering-based robot designs. The approach has great potential toward the development of robots for space exploration and operation. Future work is directed toward the design and development of versatile robots capable of intelligent control, reasoning and cooperation in communities of agents.

Design and Development Issues

The completion of the design and technology development is projected over a time frame of 10 years. It is directed toward the development of a biologically-inspired robot as an intelligent agent for space operations. Our multi-disciplinary project team will focus on:

- ***Component issues***
  Artificial muscles, sensors, self-contained power, and intelligent control.
- ***Mobility and operation issues***
  Travel over even and rough terrains, transformation and versatility, maneuverability, and object manipulation.
- ***Intelligence issues***
  Autonomous nature, problem solving and reasoning, and task specialization of robots.
- ***Community of intelligent agent issues***
  Communication and reasoning among agents, interaction and reasoning with remote scientists, cooperation and problem solving.

First prototype of biologically-inspired robot (March 1999)