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GAIT DEVELOPMENT FOR THE TYROL BIPED ROBOT

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ABSTRACT

Research on biped robots is a critical step in the development of a fully functional humanoid robot that mimics human capabilities. For this purpose, two biped robots were previously designed by the robotics research group at FIU. The first biped had seven servos and essentially attempted to maintain equilibrium while walking on flat surfaces. The second biped had six servos and was also capable of walking on flat surfaces. It integrated hybrid machine vision through an on-board camera which guided the biped to follow particular objects. The third biped presented in this paper employs ten servos and is capable of walking on flat as well as inclined surfaces. The biped senses the angle of inclination and adjusts its walking pattern autonomously. Design, modeling and fabrication of this biped robot are briefly presented. Distinct gait patterns for walking on a straight path, turning right or left, backing off, walking on inclined surfaces, and transition from one pattern into another are described. Fusion of these patterns through the developed software allows the biped to accomplish more complicated walking maneuvers. Experimental tests conducted on the biped walking on flat and inclined surfaces are presented.

Keywords

Robot, Humanoid, Biped, Control, Gait.

INTRODUCTION

In the quest for development of locomotion technologies, humanoid robots have a fundamental edge over wheeled and track enabled mobile systems based on its capability to navigate a wider range of terrains. The development of a fully functional humanoid robot necessitates simultaneous progress of a wide range of technologies such as system design, locomotion principles employed, environment recognition, mode of operation and system intelligence which are all independent key issues that are to be harmonized for functional humanoid systems.

Fundamental principles of anthropomorphic walking are still being researched to design effective navigation systems capable of becoming efficient associates to humans. Research in humanoid robotics at the Robotics and Automation laboratory (FIU) addresses stability issues concerning design and control, by the development of biped robots.

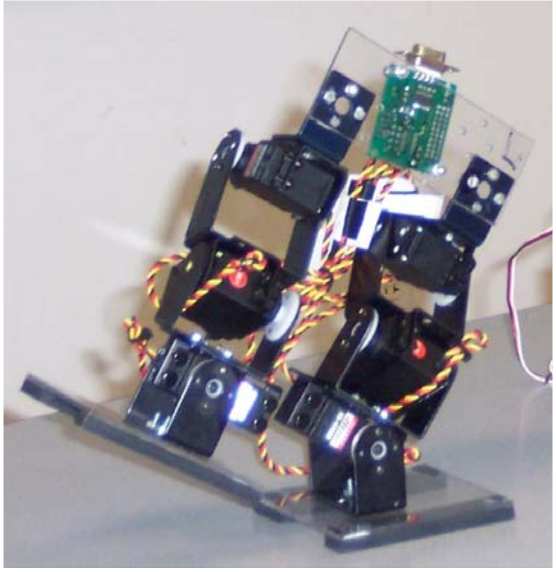

Figure 1. Clyon biped robot

The first step towards the development of a two legged walking mechanism was the Clyon project. The fundamental objective of the system was to develop simple gaits employing minimal system hardware while maintaining elements required to mimic the elegant human gait. The Clyon robot is defined by two legs that each has three degrees of freedom; a hip, a knee and ankle motion per leg. The hip and knee motions are in the same vertical plane and the ankle motion is in the horizontal plane [1]. On development of a stable walking system the project adapted to venture new frontiers by encapsulating artificial intelligence using machine vision techniques. This involved development of algorithms for hybrid machine vision for the system to be able to identify and track movements of the desired object. On successful tracking it was ensured that appropriate information was fed forward by the control module to the actuators to enable the system to follow the object being tracked. The project demonstrated efficiency of the proposed algorithms for machine vision and locomotion [2].

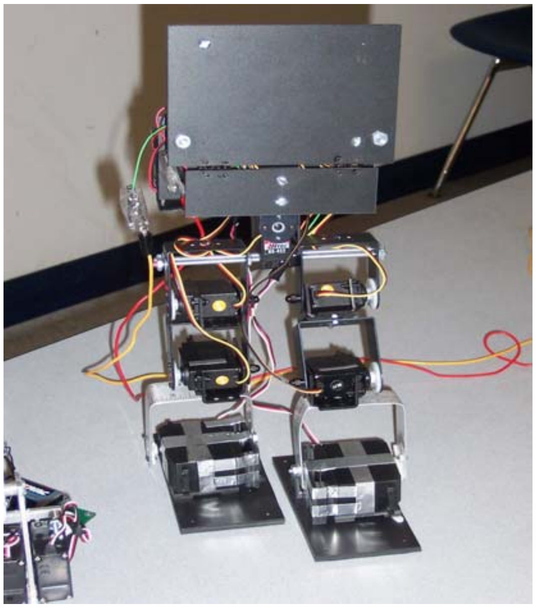
Figure 2. Cerberus biped robot

The initial Clyon project that focused on integrating machine vision with the development of simple gaits was followed by the Cerberus which focused on developing significantly more challenging gaits with easier system control. The Cerberus biped robot had eight degrees-of-freedom actuated by eight servos. Each leg has three servos, one servo at the waist and one to actuate the arms. The waist joint is used to shift the center of gravity to maintain balance as the robot moves in different gaits. The gait solver developed for the Cerberus system included the facility of describing the robot's gait on screen graphically, which is then converted into a code that is sent to the actuators of the system. This approach significantly saves time and eases software development in defining new gaits for the robot. The Cerberus biped robot was enabled to be controlled through a wireless mode via a remote control [3].

Although both the previous versions of biped robots developed were capable of executing basic gaits, they were limited to navigating on flat surfaces alone. The present biped robot, Tyrol, is designed, simulated, fabricated and experimentally tested to navigate flat and inclined surfaces. Alternative algorithms are developed to minimize actuation thereby making the system energy efficient. Gait development for the Tyrol biped robot addresses gait transitions from flat to inclined surfaces for autonomous operation.

This paper is organized as follows: The mechanical design and simulation of the designed system is detailed initially. The hardware employed for prototype fabrication for experimental testing is then briefed. Prior to experimental testing of the biped robot, gait synthesis for the system and the system's motion analysis is detailed. Gait development which includes experimental testing for the fabricated system is the presented.

SYSTEM DESIGN

Several conceptual biped robots were designed and modeled prior to developing the final design. The parameters of interest that were altered are the joint configurations and their orientation, actuator design, body masses, inertia and geometry. The variation of the above factors have a direct bearing on the displacements, velocities, forces and torques experienced by the system, which influence both the mechanical design and control of the biped robot.

The mechanical model for the Tyrol biped robot was designed using SolidWorks. In order to ensure that the simulation results are as accurate as possible, the design specifications were chosen with particular detail [4].

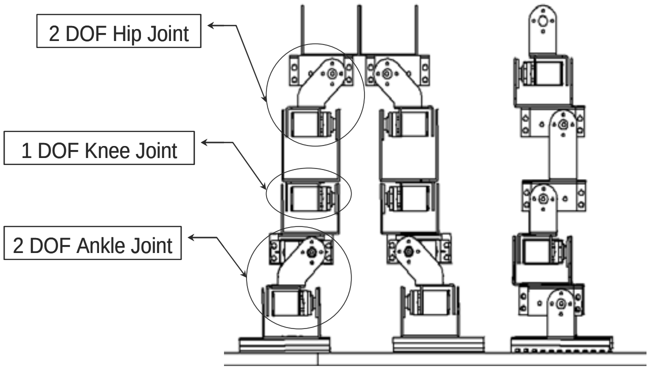

Figure 3. CAD Model of the Tyrol biped robot

The biped robot Tyrol developed in this work has a pitch joint at the hip to accommodate the tilt at the pelvis. The hip includes a roll joint to allow for lateral displacement as well as a minimum foot clearance desired by the gait patterns. Knee and ankle joint interaction is achieved using pitch joints in the hip, knee and ankle. A roll joint is also envisioned in the ankle to avoid landing on the edge of the foot. This provides us with five degrees of freedom (DOF) on each leg; with the hip and ankle joints comprising of two driven axes each while the knee joint is driven by a single axis. Hence, based on this description, a framework for designing a biped robot equipped with a total of ten driven joints is undertaken [5].

SIMULATION

Professional simulation software packages have become powerful testing and prototyping tools. Several rigid-body linkage design and simulation tools are available in industry. The choice of using any particular software relies on its computational capability, complexity of use, cost and specific toolbox availability. Almost all software packages are complemented with toolboxes for specific areas of interest. The task desired in this work is to simulate rigid-body kinematics for the biped robot. Free ODE's (Open Dynamic Engines) are available for simulation of legged creatures, ground vehicles and moving objects in Virtual Reality (VR) environments. Although advanced joint features and in-built collision detection is available in these packages, they are limited in precision design of components that generally contain built-in modules [6-10]. The simulation analysis for the Tyrol biped robot was performed in a motion development toolbox named COSMOSMotion, which employs physics-based simulation utilizing assembly information from SolidWorks.

The chief objective of the simulation stage of this biped robot development is to obtain statically stable gaits to validate the designed system. The development of gaits in the simulation phase involves complexity of system control as well as the accuracy and mode of computation the software uses. Simulation for the Tyrol biped robot was done based on trial and error methods. In order to generate statically stable gaits, motion parameters such as the robot configuration of specific links (displacements) with respect to the origin were fed into the motion solver employed by COSMOSMotion. The spline motion solver employed by COSMOSMotion interpolates the inputted discrete data by using cubic and akima splines to generate continuous motion. This resulted in emerging displacements and velocities for continuous motion of the system. Based on the obtained simulation trajectories for each joint, the displacement parameters were calibrated to actuator specifications for experimental testing of the biped robot. Successful simulation of the Tyrol biped robot necessitated the need for the fabrication of the designed system for experimental testing.

SYSTEM HARDWARE

The Tyrol biped robot accommodates minimal hardware to execute basic stages of navigation for flat and inclined surfaces. The design structure and components employed allow easy modifications to accommodate the interest of the researcher and the manner of testing the system has to undergo. A fully functional biped robot is assembled with a combination of mechanical links, electronic actuators, microcontrollers and sensors to execute the desired task.

Although the controllers and sensors used vary depending on the objective of the task, the core structure of the system consists of mechanical links and actuators. The mechanical linkages employed in the Tyrol biped robot provide a rigid and sturdy contact among the various joints in the system. The four different kind of brackets used were the multi-purpose servo bracket, C servo bracket, long C servo bracket and offset servo brackets. All the above brackets comply with the design specifications of standard sized servo motors. The multi-purpose servo bracket provides a casement for the servo motors used to actuate the system. These brackets are widely implemented in making multi-axis joints for the system.

The two different versions of C brackets used varied in length. The shorter version of the C bracket is used to connect the knee joint to the ankle joint, and ankle joint to the foot. These C brackets are connected directly with the hub of the servomotor and provide effective knee-ankle interaction. The long C bracket is used as a link between the hip and knee joints of the system. The step length of the system is bound by the length of this link. Similar to the shorter version of the C bracket, this link is directly connected to the hub of the servomotor.

Selection of actuators has a significant bearing on the outcome of the performance of the biped robot. The weight of the actuator contributes a significant sum to the total weight of the system which has a direct bearing on balance issues. DC servomotors were chosen as actuators for the Tyrol biped robot as they are small, affordable and relatively powerful for their size thereby providing a good option for smaller robot designs. The DC servomotor selected for the Tyrol system is the HS5955 TG Hitec servomotor which is small in size and capable of achieving high speeds and withstanding large amount of torques. Two HS5955 digital servos are encased in multi-purpose servo brackets at the hip and ankle joints while a single servomotor serves as an actuator at the knee joint. The range of motion for these servomotors is 140° and is capable of a 180° rotation after programming with a Digital Servo Programmer (DSP-01).

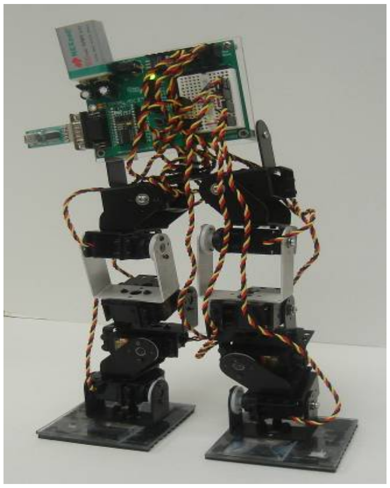

Figure 4. Fabricated Model of Tyrol

Microcontrollers maintain a relationship between the actuators and their consequential movements using measurements made by sensors. The sequence of steps required to execute a task are planned and controlled with respect to the task being performed. The microcontroller enables the user to act as a guiding system, through which the user is capable of programming the robot to adapt its actions in response to changes in the external environment. Each higher level task is accomplished by decomposing them into a sequence of lower level commands based on the strategic model of the task.

Several controllers were available from which an inexpensive and powerful microcontroller was chosen to program the Tyrol system. In the Tyrol system development, a 16-pin DIP (Dual Inline Package) Board of Education control board is used with a Basic Stamp 2 processor. The controller board used in this work essentially governs the system based on the instructions provided by the user. It acts as an interface between the user and the biped robot providing a platform for the processor to compute the user's instructions. A BASIC Stamp 2 (BS2) processor, which is compatible with the Board of Education control board, is used to develop gaits for the Tyrol biped robot. The biped's processing requirements are provided by the BS2 microcontroller, a relatively inexpensive platform commonly used in robotics projects. It encompasses a PIC16C57 processor developed by Microchip Technology Inc. The BS2 processor is programmed using PBASIC, a hybrid programming language used to control Parallax, Inc. products.

Sensors were required for the Tyrol biped robot to detect changes in the navigating terrain, as navigating inclined surfaces is a significant element in the developmental objective of this system. Accelerometers are used in a wide range of applications such as tilt sensing, rotational position sensing and movement/lack of movement sensing. The Tyrol biped robot employs a Memsic 2125 dual-axis accelerometer to detect and calibrate the change in inclination of the navigating terrain. The working principle of the accelerometer is based on temperature variation detected by thermopiles. Based on the orientation of the Memsic 2125, it is capable of sensing forward/backward, left/right and up/down motion. The integration of the Memsic 2125 with the adopted microcontroller is simple and easy to use. The pulse outputs obtained from the accelerometer were calibrated and computed by the onboard processor to obtain tilt of the system in degrees.

The fabricated model of the biped robot is shown in Figure 4. The weight of the complete robot structure is slightly below 1 kg and it stands 1 ft tall with the control board mounted on it.

GAIT SYNTHESIS

Methodology

Gait synthesis for the Tyrol biped robot was developed based on the principles of static stability. The principle followed in developing stable static gaits is based upon the projection of center of gravity of the robot on the ground remaining within the foot support area. The support area is either the foot surface in case of one supporting leg or the minimum convex area containing both foot surfaces in case both feet are on the ground. These are referred to as single- and double-support phases, respectively. Inertial forces are considered to be negligible while adapting a statically stable gait [5]. The fundamental gaits to be developed for bipedal robots concern the robot's ability to walk, run, turn, climb stairs, etc.

Navigation for any system can be characterized by several distinct functions and routines, which can be integrated based on the navigating terrain and the objective of the task. Gait development for the Tyrol biped robot is simple as the design structure of the system is symmetric. A gait is developed for one leg and executing its symmetric opposite on the other leg for a continuous gait pattern [5]. The gait synthesis approach adapted for the Tyrol biped robot involved developing fundamental walking and turning patterns for flat surfaces. On successful development of these algorithms, gait development for inclined surfaces is initiated. Sensor data from the accelerometer is calibrated to detect the slope of the navigating terrain for inclined surface navigation. Gait transition from flat to inclined surfaces is then addressed. Feasibility of integration of these algorithms were based on similar robot configuration at crucial stages of the gait and the navigating terrain. The developed gait synthesis is then experimentally tested on the fabricated model of Tyrol.

Motion Analysis

The gaits developed for the simulation stages of the Tyrol biped robot was based on static walking. An analysis of the simulation results provides vital insights for experimental gait development on the fabricated prototype of the Tyrol biped robot. Motion analysis for the Tyrol biped robot comprises the analysis of the displacement, velocity and acceleration of the hip, knee and ankle joints with respect to various stages of the developed gait (time).

The linear displacements of the right and left hip joints are shown in Figure 5. A symmetric opposite of the displacement of the left hip joint is seen in the displacement chart of the right hip joint. The spike in the motion trajectories observed comprise the process of shifting the center of gravity of the system. This process consists of the biped robot swaying sideways in a cyclic pattern ensuring a continuous gait pattern.

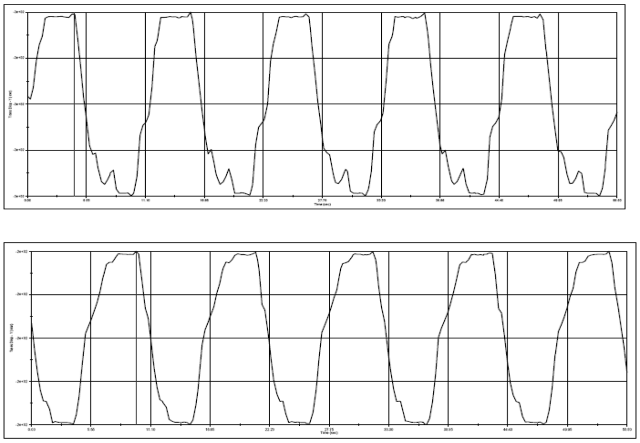

Figure 5. Linear displacements of the right (top) and left hip joints of Tyrol

The velocities of the hip joints on both limbs are shown in Figure 6. It is to be noticed that the velocities of both joints are close in magnitude. The charts are noticed to have smaller intermittent spikes and a periodic spike after each step cycle.

These validate the biped robot stabilizing during intermediate stages of walking and come to a brief halt (larger fluctuations) after a complete step cycle. The velocities of both joints are kept as close to each other as possible to achieve a continuous gait which results in smoother motions.

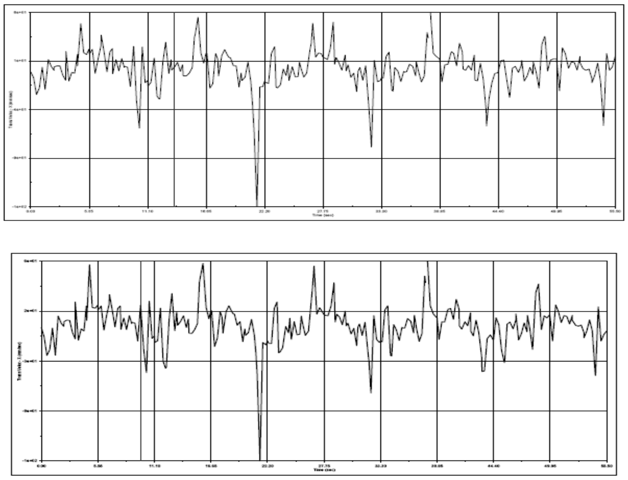

Figure 6. Velocity charts of right (top) and left hip joints

The acceleration charts for both hip joints are shown in Figure 7. Other than a huge initial fluctuation, the accelerations of the hip joints are kept at a minimum. The initial fluctuation is large as the biped robot starts its gait cycle with zero momentum.

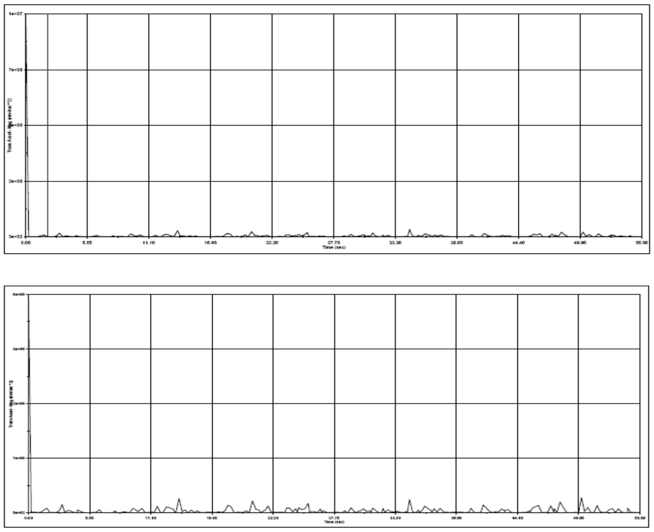

Figure 7. Acceleration charts of right (top) and left hip joints

Since the velocities of both joints are as close as possible, the acceleration of these joints is minimal. The small fluctuations observed in this chart are caused due to the Tyrol biped's recovery from static stable positions.

The linear displacements of both knee joints are shown in Figure 8. A large spike is generated in the motion trajectory of the knee joint on one leg. This is followed by an inverted symmetric spike in the next step cycle. The above processes represent the flexion and inflexion of the knee.

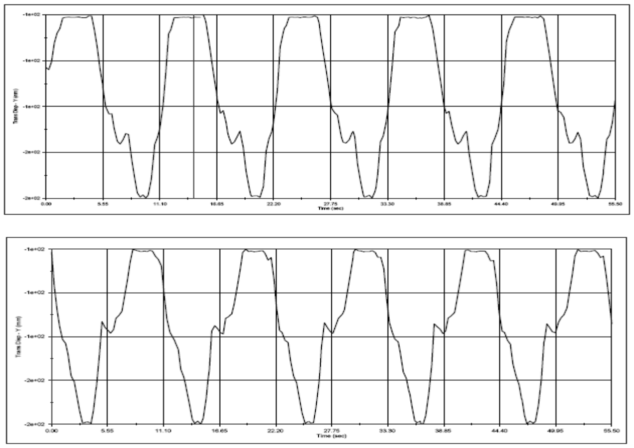

Figure 8. Linear displacement of the right (top) and left knee joints

The velocity distribution of the right and left knee joints is shown in Figure 9. Although the frequencies of velocity adjustments for the two knee joints are similar, it is to be noted that the magnitude of velocities on both legs is different. This difference causes the biped robot to turn around the leg whose knee joint has a lower velocity magnitude.

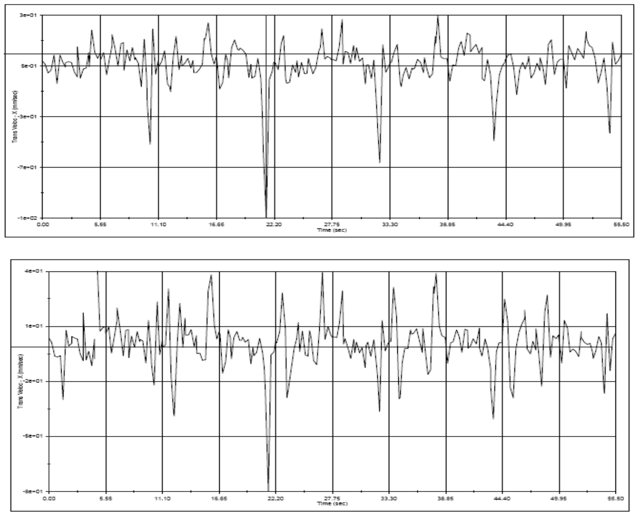

Figure 9. Velocity distribution of the right (top) and left knee joints

The velocity magnitude is expected to remain same on both knee joints for perfectly straight walking. Considering that the velocity fluctuations are small and occur only during transitional stages of the gait, the acceleration of both knee joints is minimum providing smooth and elegant motion.

The linear displacements of the ankle joints of both limbs are shown in Figure 10. These fluctuations represent a continuous shift between the single support phase and the double support phase of the Tyrol robot. Similar to previously mentioned results, a symmetric pattern is observed which is periodic in nature.

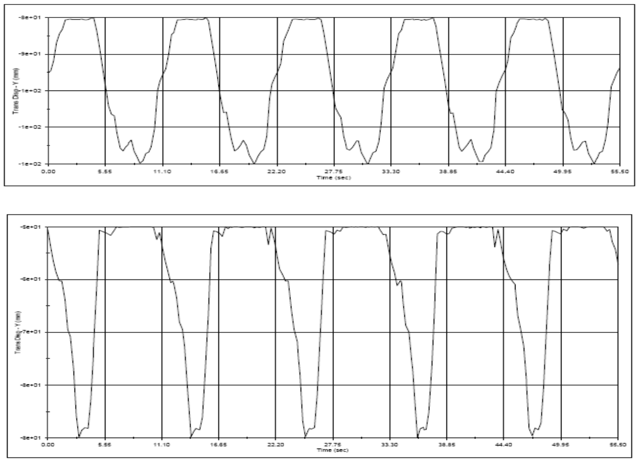

Figure 10. Linear displacement of the right (top) and left ankle joints

The displacement fluctuations for the ankle joints are broader and represent a step cycle during which the particular limb is firmly footed while the other limb is in its swing phase.

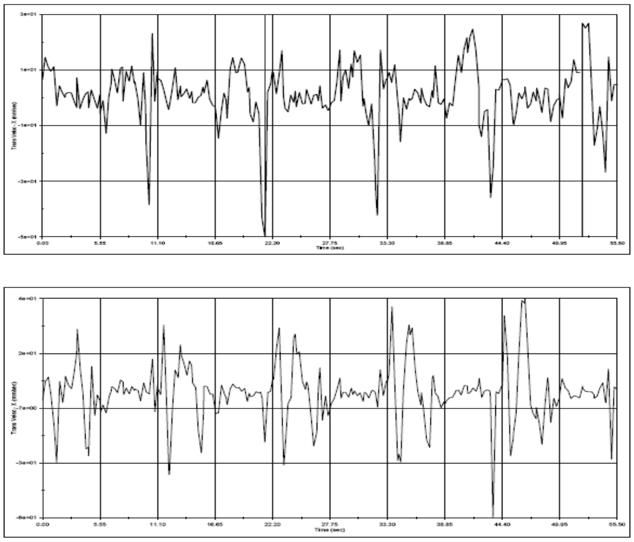

Figure 11. Velocity distribution of the right (top) and left ankle joints

The velocity distribution of the ankle joints are shown in Figure 11. Although a similar approach for foot placement was implemented on both limbs, the chart shown in Figure 11 shows minute similarity. This difference is attributed to high computational power required by the motion solver. Impact of 3-D objects with external surfaces in gravity based simulation environments yields inaccurate results either due to insufficient computational power of the computer, operating system capabilities or the simulation software itself. This detailed difference in outcome of simulation results and experimental results is termed as reality gap.

GAIT DEVELOPMENT

Simulation results validate the designed system to be capable of static walking thereby revealing key features for gait development of the Tyrol biped robot. Initial experiments on the system were performed with the simulation results obtained. The motion trajectories of the joints of the system were calibrated into actuator specifications which serve as input parameters for experimental testing of the system. On successful development of these initial gaits, the system was programmed for more robust locomotion while navigating flat and inclined surfaces. The various gaits developed and their experimental testing are explained in this section.

Walking Gaits

The walking gait developed for the Tyrol biped comprises of a sequence of strides. A continuous walking motion is achieved with the repetition of the developed periodic cycle.

The system is initially erect with all the actuators making the biped robot stable and balanced with both feet on the ground. For the system to advance to its next state, a shift in center of gravity is necessitated. This is achieved utilizing different methods for the Tyrol biped robot.

It involves a series of combinations with the hip and ankle joint actuation, or for faster modes of walking, the hip joints alone. The process involves the hip joint lifting one leg and the ankle joint of the other leg ensuring that the system is stable at all times. A shift in center of gravity is also achieved with the hip and ankle joints of the same leg coordinating with each other. However, in this case the ankle joint assists in lifting one leg higher than the other while the hip joint ensures that the system is stable throughout the entire process. With both of the above methods, a shift in the center of gravity of the system is achieved. The above process transfers the biped robot from a double support phase to a single support phase.

With one leg firmly footed, the other leg is utilized to move the system forward. The link between the hip joint and the knee governs the step length the system is capable of achieving. The pitch joint in the hip is actuated to move the leg forward while the knee joint assists the system to bring down the leg. The pitch joint in the ankle ensures that the Tyrol biped robot achieves appropriate foot placement. This process brings the Tyrol robot back from a single support phase to a double support phase. The shift in COG back to the center is simultaneously executed with the biped robot interacting with the ground forces to propel the system forward. This shift in COG back to the center is achieved with the methods explained previously. It is to be achieved with the same principle followed while moving the COG off center but to be implemented on the other leg. The system's interaction with ground reaction forces propels Tyrol forward which is achieved with the flexion and inflexion of the knee joint. As the biped robot moves forward, the COG is shifted to the other side with the system again moving into a single support phase. The above transition from a single support to double support phase is continuously repeated to achieve a stable walking gait for the robot.

Turning Gaits

The system's ability to make a complete turn involves a series of motions which are periodic in nature. The biped robot turns in small angles until the desired state is attained. The angle the biped robot is to turn can therefore be attuned depending on the task being performed.

In the initial state, the Tyrol biped robot has both its feet firmly footed on the ground. Turning of the system is achieved through the reactive forces developed with the ground. The knee-ankle joint interaction is utilized for the system to swivel around the inner leg in the direction of interest. The flexion and inflexion of the knee assists in propelling the system forward while the ankle joint compensates for the stability of the system. The actuators in the knee joint are required to turn larger degrees in comparison to the hip and ankle joints. The ankle joint is actuated for a series of smaller degrees. For every single actuation of the knee joint, the ankle joint is actuated for a series of smaller angles. The knee-ankle joint interaction is achieved based on the repetition of the above process.

Inclined Surface Navigation

Walking gaits on sloped surfaces were developed with modifications made in the gaits developed for walking on flat surfaces. It requires that the swing limb to be lifted off the ground completely at the beginning of the step cycle and land at the end of it. Hence, shifting the COG of the system was possible using the ankle and hip joints of opposite legs alone, unlike several possibilities that existed for walking on flat surfaces. Readings from the sensor were continuously fed forwarded to joints, which were parameterized to accurate actuator positions. All joint positions of the biped robot incorporated the shift in angle of the sloped surface.

The requirement for repeatability of the step cycle demands the initial posture and velocities to be identical to those at the end of the step. The horizontal displacements of the hip during the single and double support phases were identical to ensure continuity of the gait. During locomotion, the swing limb contacts the ground, which causes impact that results in sudden changes in the joint angular velocities. Hence, the velocity of the foot of the swing limb was decreased before impact, which reduced the sudden jump in the joint angular velocities for smoother navigation.

Gait Transition

Gait transition is a motion pattern that is inherently acyclic, beginning at a phase angle and robot configuration found in one gait and ending in a phase angle and robot configuration in another gait [11]. Gait transition for the prototype system includes navigation for autonomous operation in two different terrains. They are executed based on information acquired from the accelerometer onboard. The Tyrol biped robot is programmed to round off the surface inclination to its closest integer for calibration purposes thereby providing better actuation for the robot's joints.

Conventional gait transition theory follows the principle of maintaining motion while changing a gait's parameters from one gait to another over a finite period of time. This is achieved by either altering the speed of certain joints or the angle of rotation of a specific link. Gait parameters are changed by manipulating the above processes until transition is complete. However, all gaits do not have similar robot configurations at different stages of the developed gaits. In order to formulate gait transitions, the leg in flight is manipulated to move faster or slower than normal until the desired robot configuration is achieved. When the desired robot configuration is achieved, the biped robot is able to continue navigation providing a smooth transition from one gait to another.

Different gaits developed for the Tyrol biped robot are merged at critical points where the posture and velocities of joints are similar. In order to generate useful transitions, it is important to assess different possibilities and their feasibility in advance. The biped robot when making transitions from a flat to an inclined surface starts navigating based on walking algorithms generated for flat surfaces until a change in the navigating terrain is detected. On detection of a change in terrain, the robot configuration is changed accordingly to a similar and existing robot configuration for navigation on inclined surfaces. Gait transition from flat to sloped surfaces is achieved when the biped robot is capable of determining the inclination and the point where there is a change of terrain. This is user defined enabling the system for uninterrupted navigation.

CONCLUSIONS AND FUTURE WORK

A ten degree-of-freedom biped robot has been designed, modeled, simulated and fabricated for experimental testing of several gaits. The gaits developed in this work have included walking on level surfaces, turning, as well as climbing inclined surfaces. Overall, the biped robot performed well and the gaits were tested successfully. This effort has also demonstrated progress in the development of a complete humanoid robot, which is seen as a challenging goal in the development of robotic systems.

The Tyrol system presented in this paper will however benefit from using more sophisticated hardware for even more elaborate gait synthesis. This will undoubtedly increase the complexity of control and the cost of the biped robot.

Factors such as computational power to perform gait planning and ability to obtain accurate, timely sensor information play major roles in successful gait execution. The computational processing power of the system can be augmented by utilizing more complex microcontrollers and sensors. Additional sensors may be utilized in devising methods to detect and relay precise information concerning distance and change in inclination of the terrain the system is navigating in.

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