# TYROL: EVOLUTION OF A 10-AXIS BIPED ROBOT

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## ABSTRACT
This paper presents work demonstrating the evolution of a biped robot named Tyrol from a simulation environment to physical realization. For the past few years, humanoid robot development has been receiving increasing interest by several research groups. The design of this class of robots is quite challenging because of a variety of reasons such as the high number of degrees of freedom involved, balancing issues, power to weight ratio, and complexity of their control. By studying the development of a biped robot, this work addresses humanoid robot design and control in a bottom-up approach. For this purpose, a ten-degree-of-freedom biped robot concept was developed, modeled and constructed. Different gait algorithms have been developed for the biped robot to navigate on flat and inclined surfaces.

## Keywords
Robot, Humanoid, Biped, Control, Gait.

## 1. INTRODUCTION
The process of designing and simulating systems before fabrication has been a standard approach used by robotics engineers. This has led to a generation of better robotic systems and continues to do so [1-4]. A simulation of the multi-degree-of-freedom humanoid robot allows the designer to illustrate and visualize a robot's design before fabricating the system. Constraints in the design can be overcome and design can be altered providing means to a more efficient system. Control parameters that are fed into the fabricated model are generally more accurate after the simulation of the robotic system. Similarly, walking principles and new gaits can be tested and optimized at an early design stage allowing a leeway for modification. This increases flexibility and decreases workloads for designers. These arguments are especially important for humanoid robots or bipeds where control of multiple joints proves to be quite a challenge.

One among the many challenging tasks is to generate a stable walking gait for biped robots. The development of gaits in the simulation phase is bound by the accuracy and mode of computation the software uses. Biped robots navigate using discreet footholds and interactive joint forces, whose simulation may require relatively high computational power. Compromising accuracy at any stage during the simulation is generally noticed when the fabricated model is tested. Brooks [5] states that one of the fundamental reasons for avoiding robot simulations is that there is a great danger that the simulations will not match the real world. This difference between the simulated and real world is sometimes referred to as the reality gap [6].

This paper presents the simulation and gait development of a biped robot. After successful simulations, the designed model was fabricated and tested. Gait algorithms that were developed to be tested on the fabricated model are based on stable static walking concept, which means that the system remains statically stable at all phases in a gait. Gait development for the biped robot was accomplished for both flat and inclined surfaces. Individual algorithms developed are periodic or cyclic. These individual motion patterns are then integrated to perform a desired task provided that they are feasible. Navigation from flat surfaces to inclined surfaces or vice-versa involves modification of the developed algorithms based on the feedback received from sensors. These are more complex in nature as they involve fusing algorithms developed for two different planes in comparison to unification of algorithms developed for flat surfaces alone.

The paper is organized as follows: An outline of the projected system and mechanical model of the biped robot is detailed in Section 2. The hardware required for fabricating the designed model is presented in Section 3. The development of a walking gait in a simulation environment and the mode of computation is described in Section 4. In Section 5, gait development for the Tyrol biped robot and the algorithms are explained. Finally, Section 6 summarizes conclusions and future work.

## 2. SYSTEM DESCRIPTION
In order to develop humanoid robots, an empirical structure of the human form is chosen as the fundamental mechanical design. Allocation of the number of joints and their location were specified with respect to the anthropomorphic framework. An investigation into the mechanisms of walking reveals a few major determinants that characterize the human walking motion. They are the pelvic tilt, knee flexion, knee-ankle joint interaction, and lateral displacement of the pelvis [7]. The incorporation of the above determinants shapes the outcome of the final design.

The biped robot Tyrol developed in this work has a roll joint at the hip to accommodate the tilt at the pelvis. The hip includes a pitch 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 (Figures 1 and 2). Hence, based on this description, a framework for designing a biped robot equipped with a total of ten driven joints is undertaken.

The mechanical model was designed and simulated using the software package offered by Solidworks. It presents an efficient simulation and animation environment for motion analysis known as Cosmos Motion. In order to ensure that the simulation results are as accurate as possible, the design specifications were chosen with particular detail. The components designed and employed in this system comply with standards maintained in the market. The range of motion of a few joints is limited when assembled owing to the outcome of the final design of the biped robot.

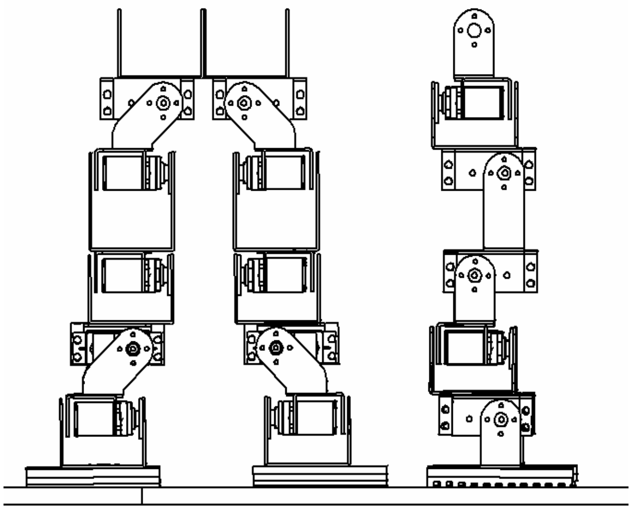

**Figure 1. Tyrol's Mechanical Model Front View (L) and Side view (R)**

The ankle joint has 2 DOF, which allow motion in the sagittal and the lateral plane. The range of motion in the sagittal plane is between +90º and -50º, and +40º and -70º in the lateral plane. The mobility for the knee joint is +140º in the sagittal plane. The hip joint is similar in design to the ankle. Similar to the ankle joint, it is capable of moving in the sagittal and lateral planes. In this case, the range of motion is from +70º to -70º for movement in the sagittal plane, and between +40º and -70º for lateral plane. Stable and satisfactory motion range is achieved for the biped with the above set of values.

## 3. SYSTEM HARDWARE

The fabricated model of the biped robot is shown in Figure 2. The weight of the complete robot structure is below 1 kg (without supply batteries) and it stands 1 ft tall with the control board mounted on it. Each individual component is explained in detail in the following subsections.

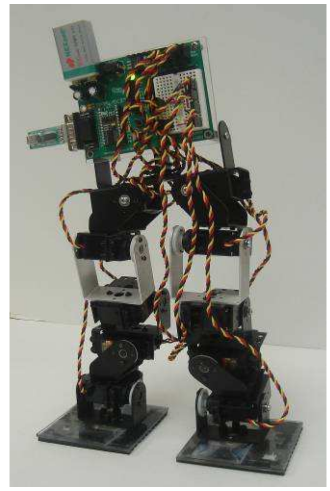

**Figure 2. Fabricated Model of Tyrol**

### 3.1 Actuators

The design of the actuator is significant as its weight constitutes around 60% of the total machine mass [7]. An ideal actuator for the system would be one with the highest power-to-weight ratio. Contemporary actuators are small in size and are capable of achieving high speeds and withstanding large torques. The actuators used in the design of this system were in accordance with the standard sized servomotors developed by Hi-tec, Inc.

**Figure 3. HS5955 Hi-tec Servo**

As described earlier, the biped robot's each leg has one actuator at the knee joint and two actuators at the hip and ankle joints each. The biped has 10 degrees of freedom (DOF) in total; each of the joints is powered by a Hi-tec HS5955 digital servo. This servo comes in a standard size and has a compact design. Its operating voltage range is between 4.8-6.0 VDC. The power-to-weight ratio of the HS5955 servomotor is relatively high as the servo weighs 2.18 oz and is capable of a standalone torque of 333 oz-in. The range of motion is 140° and is capable of a 180° rotation after programming with a Digital Servo Programmer (DSP-01). The servomotor is capable of a 60° rotation in 0.15 sec.

### 3.2 Controller

The controller used in this work essentially governs the system based on the instructions provided by the user. It receives its power through an external battery from which the actuators are driven. It is imperative that the actuator is able to draw the desired power from the control board for it to operate at peak conditions. Several controllers were available from which an inexpensive and powerful micro-controller was chosen for programming the system.

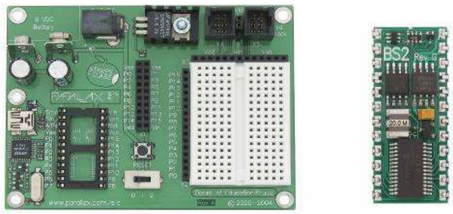

**Figure 4. Board of Education Micro-controller (L) and BS2 Processor (R) [8]**

The Basic Stamp 2 (BS2) processor shown in Figure 4 is a 16-pin DIP (Dual Inline Package) module that is compatible with the Board of Education by Parallax. The biped's processing requirements are provided by the BS2 micro-controller, a relatively inexpensive platform commonly used in robotics projects. The controller's specifications are shown in Table 1 [8]. It is able to control and monitor switches, timers, motors, sensors, relays and valves. The BS2 is programmed using Pbasic, a programming environment used to control Parallax, Inc. products.

**Table 1. BS2 Microcontroller Specs**

| | |
|---|---|
| Processor Speed | 20 MHz |
| Program Execution Speed | ~4,000 instructions/sec. |
| RAM Size | 32 Bytes (6 I/O, 26 Variable) |
| EEPROM Size | 2K Bytes, ~500 instructions |
| I/O Pins | 16 +2 Dedicated Serial |
| Voltage Requirements | 5 - 15 vdc |
| Current Draw at 5V | 3 mA Run / 50 µA Sleep |

## 3.3 Sensors

Efficient biped walking is possible through system's successful interaction with its surroundings. The integration of sensors in the present system allows the biped robot to monitor and regulate its physical state with respect to its environs. Sensors are employed on this system to monitor the biped robot's internal and external parameters. Force and pressure sensors are mounted on the layered structure of the feet to measure interaction forces and torques under system operation. They are able to continually sense the intensity of interaction over an area within which there is a spatial resolution.

**Figure 5. QT113-D Touch Sensor [9]**

An inexpensive and relatively simple QT113-D touch sensor (Figure 5) that is capable of sensing fields through dielectric surfaces is used in this system. The QT113-D touch sensor offers auto-calibration, drift compensation, recalibration timeouts and a variety of response times. More accurate sensing is achieved with the this sensor as it automatically adapts to accumulated dirt, moisture and temperature variations.

The other sensor installed in the biped system is the accelerometer. The accelerometer is used to measure the kinematic parameters of the robot such as the joint positions, velocities and accelerations. Based on the information obtained from these sensors, the controller is programmed to alter gait performance accordingly. The element of drift associated with accelerometers builds up errors into the reading over a period of time, which has to be accounted for.

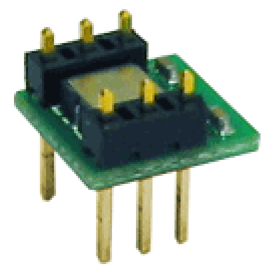

**Figure 6. Memsic 2125 Dual-axis Accelerometer [10]**

A Memsic 2125 dual axis accelerometer made by Parallax, Inc. is used to measure the tilt and orientation of the system (Figure 6). It is capable of measuring 0 to ±3 g on either axis and is fully temperature compensated over 0°C to 70° C range. The sensor transmits a pulse output of g-force for the X- and Y-axes along with an analog output of the temperature. The data obtained from it is fused with other sensors to determine the orientation and state of the biped robot.

# 4. DEVELOPMENT OF A WALKING GAIT

## 4.1 Walking Methodology

From a control theory point of view, bipedal walking robots are more difficult to deal with than wheeled and multi-legged robots. The most fundamental aspects for bipedal robots concern their motion behaviors, which allow the robot to walk, run, turn, climb stairs, etc. In this work, stable static walking of a biped robot is considered. Static walking assumes that the robot is statically stable at all moments during the gait. This means that, at any time, if the motion of the system comes to a halt, then the robot will indefinitely stay in a stable position. The principle of static walking 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.

## 4.2 Simulation

A 10-DOF mechanical model of Tyrol that was designed earlier is simulated using Cosmos Motion. The model has ten revolute joints. Each of the joints is powered by an actuator where motion parameters are fed to the system. The system is controlled by the basic principle of static walking by keeping the center of gravity of the biped robot within the support area of the system.

Cosmos Motion provides multiple options of defining input parameters for forces and motion using built-in functions or by creating user-defined functions. The system was controlled using the spline function which allows the user to define a motion generator. A motion generator is defined by specifying discrete displacement values of specific links at specific points of time. Cosmos Motion provides two types of splines; Akima (AKISPL) and Cubic spline (CUBSPL), for interpolation while solving motion or force equations.  During the simulation, the Cosmos Motion solver interpolates discrete points using one of the two types of splines, depending on the user's choice, which results in a smooth continuous curve [11].

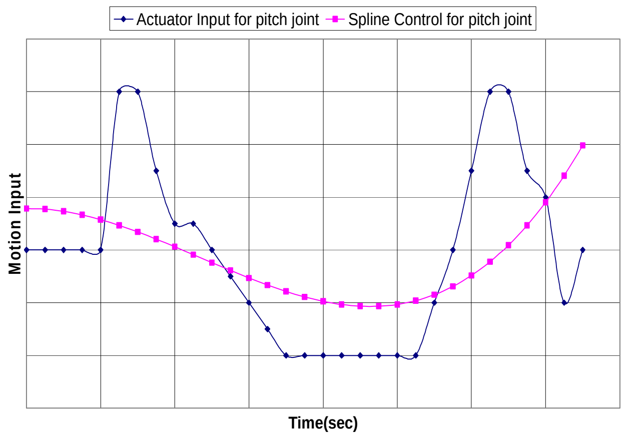


**Figure 7. Trajectory of the ankle joint**

The Akima interpolation is a local fit. Local methods require information only about points in the vicinity of the interval being interpolated to define the coefficients of the cubic polynomial. This means that each data point in an Akima spline only affects the nearby portion of the curve. Since it uses local methods, Akima interpolation technique is very fast.

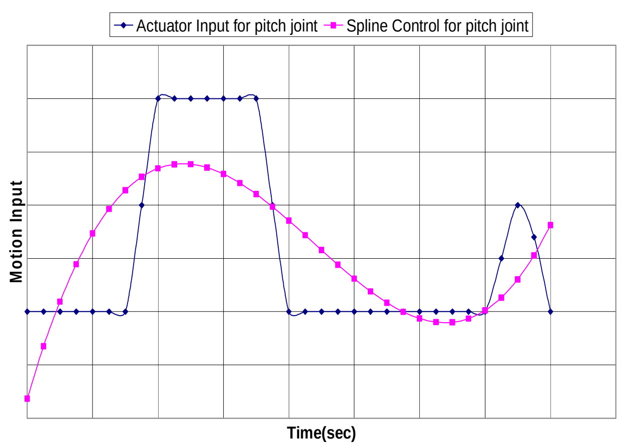


**Figure 8. Trajectory of the knee joint**

Akima Spline function produces good results for the value of the function being approximated. It returns acceptable estimates for the first derivative of the approximated function when the data points are evenly spaced. In instances where the data points are unevenly spaced, the estimate of the first derivative may have a large error. In all cases, the second derivative of the function approximated is unreliable; as higher-order numerical derivatives in general become unstable.

The Cubic spline interpolation is a global fit. Global methods use all the given points to calculate the coefficients for all of the intervals in question simultaneously. Therefore, each data point affects the entire cubic spline.

Both global and local methods work well on smoothly-curving functions. CUBSPL, although not as fast as AKISPL, always produces good results for the value of the function being approximated, as well as its first and second derivatives. The data points did not have to be evenly spaced. The solution process often requires estimates of derivatives of the functions being defined. In general, the smoother a derivative is, the easier it is for the solution process to converge.

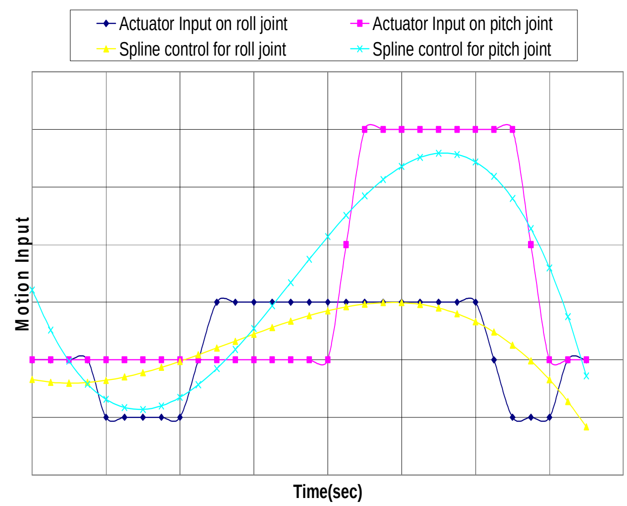


**Figure 9. Trajectory of the hip joint**

Smooth (continuous) second derivatives are important if the spline is used in a motion. The second derivative is the acceleration enforced by the motion, which defines the reaction force required to drive the motion. A discontinuity in the second derivative implies a discontinuity in the acceleration, and; therefore, in the reaction force. This can cause poor solver performance or even failure to converge at the point of discontinuity [11].

Both methods were implemented on the system to verify results. The input simulation parameters for actuator control and the spline control generated by the simulation software for the ankle, knee and hip joints are shown in Figures  7, 8 and 9. Variations in the motion of the biped robot were minute and unnoticeable. Computation time was remarkably shorter for the Akima spline compared to the cubic spline. Based on the principle of ZMP [12, 13], a successful simulation of stable static walking has been implemented on the designed system.

## 5. GAITS

### 5.1 System Navigation

The objective of designing a biped system and implementing walking techniques is to develop a stable mobile system capable of efficient navigation. Simulation results have shown that the designed biped system is capable of statically stable navigation. The designed system was then fabricated corresponding to the hardware mentioned under Section 2.

An efficient navigation system, besides possessing other capabilities, should be able to traverse different terrains with good mobility. Navigation for any system can be categorized into several basic functions and routines, which are integrated to generate better gaits for different terrains. The initial course of gait development rests in generating fundamental walking patterns that are practical and functional when integrated with other gaits. Fundamental gaits to be developed on the designed system include walking – forward and backward; turning – left and right; and traversing inclined surfaces. Each of the above gaits is a significant development towards system navigation as they can be integrated with each other depending upon their feasibility and structure of the terrain improving system performance.

## 5.2 Walking

The design of the biped robot is symmetric which makes gait development simpler. An algorithm is defined and executed on one leg and its symmetric opposite is executed on the other leg for a complete gait pattern. Different kinds of walking gaits have been developed on the system. Each gait induces different amounts of torque and reactive forces on the joints and support ground, respectively.

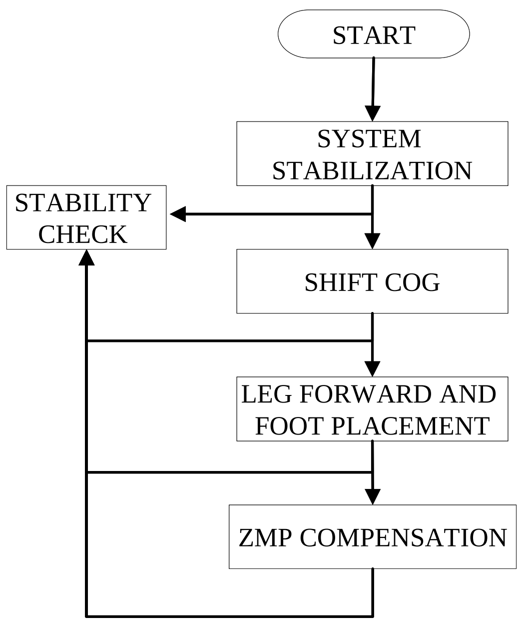


**Figure 10. Walking gait algorithm**

Tyrol's walking gait is categorized into five different stages. The first stage is when the system is stable and ready for motion. The second stage involves the shift in center of gravity (COG) of the system. The shift in COG is accomplished by controlling the roll joints in the ankle. The third stage of the gait involves forward leg motion and stable placement of the robot's feet. This stage governs the step length the robot is programmed to take. The interaction of pitch joints on the knee and ankle help in accurate placement of the feet. The interaction of ground forces with the system and the shift in center of gravity of the biped robot propel forward motion which is labeled as stage four. Stage five involves stabilization of the system for the entire process to be repeated on the other leg.

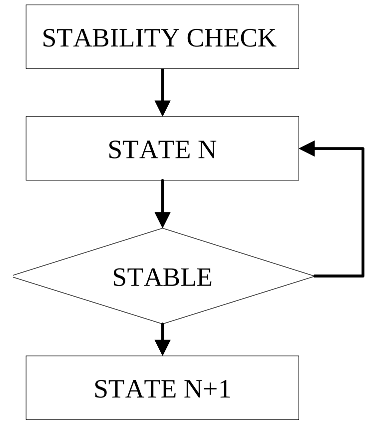


**Figure 11. Static Stability Verification**

Static walking requires that the biped is statically stable at all stages of the gait. The system verifies stability at the end of each stage and the proceeds to the next. The flowchart for the developed algorithm is shown in Figure 10.

## 5.3 Turning

Turning for the biped robot is possible through the reactive forces developed with the ground. The system's ability to make a complete turn involves sequences of motion. The biped robot turns in small angles until the desired state is accomplished. The algorithm mainly exploits the use of the knee-ankle joint interaction due to the absence of a yaw joint in the system.

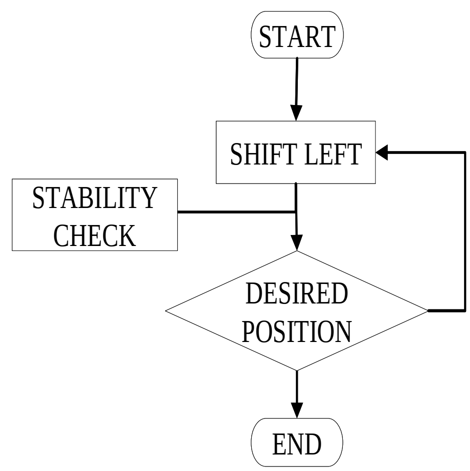


**Figure 12. Tyrol biped robot's turning gait algorithm**

In similarity to the human's turn about an axis perpendicular to the ground, the biped robot swivels about the inner leg. Both legs facilitate the motion of the other. The outer leg assists in inducing reactive forces which the inner leg compensates by moving accordingly. All intermediate states are verified for system stability. The gait algorithm which is shown in Figure 11 has been successfully implemented on the biped robot.

## 5.4 Inclined Surfaces

Navigation on inclined surfaces is made easier with the help of sensors such as inclinometers and inertial measurement units. This biped robot uses an accelerometer to enhance its navigation capabilities on inclined surfaces. Gait development for inclined surfaces requires modification of the periodic walking cycles that have been developed so far. Similarities and differences in gait patterns are noted while traversing flat and inclined surfaces. Apart from the same walking principle used to navigate these terrains, induced torques and reactive forces on the lower half of the system are significantly different.

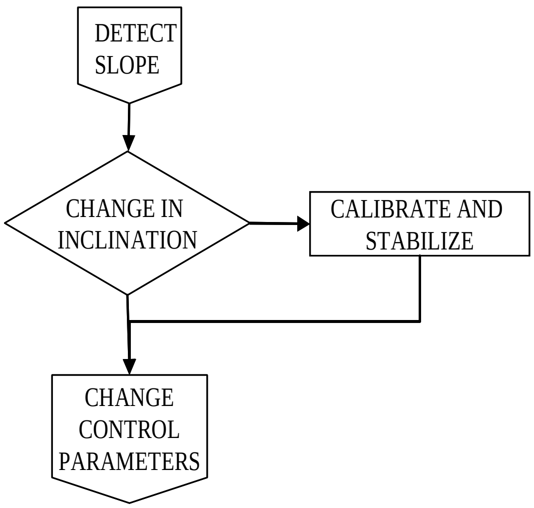


**Figure 13. Flowchart for inclined surface navigation**

Input motion parameters vary depending on the slope of the inclined surface. The system is programmed to initially detect the inclination of the terrain and stabilize accordingly. Depending on the slope, all actuator inputs are varied accordingly and the system continues navigation based on the walking algorithm mentioned in section 5.2. Inclined surfaces require more ground clearance for which this biped system is able to comply with.

## 6. CONCLUSIONS

In this paper, a ten-DOF biped robot Tyrol has been proposed, simulated and constructed. Simulation of the biped robot involves a lot of time and complexity. The spline control generated for actuation of the system is bound by the software's computational capability. Higher degree polynomial fittings could result in further optimizations of the simulation algorithms developed.

The fabricated system was initially tested based on the motion algorithms generated for simulation. System performance was observed to be close in resemblance to simulation results. Precision modeling and simulation greatly assisted in narrowing the reality gap. The sensors mounted on the system had to be calibrated and tested for accurate feedback. The touch sensor employed was observed to be quite sensitive and needed frequent monitoring. Also, drift in the accelerometer had to be compensated at regular periods.

Further gait development and different modes of basic navigation modes were also tested on the biped to optimize system performance. The system is observed to be capable of robust navigation on flat and inclined surface.

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