New Steps in the Development of the Two Legged Robot CENTAUROB

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Abstract

In this paper the development of a new prototype for a statically stable robot system is described. Special feature of this system is the use of Steward-platforms as leg structures. Based on the evaluation of the first prototype, the design of a new set-up is shown which comprises reengineered actuators and sensor modules and an optimized mechanical structure. Since the robots is supposed to interact and move independently, biped walking and control concepts are discussed that will be implemented.

Introduction

Robotic devices already succeeded in a broad range of industrial applications. Now, the service robots get into the spotlight of research and first concepts are already implemented. In order to easily incorporate these robots in the human environment, the high-grade flexible human anatomy often serves as an example. Models of robots that use this anthropomorphic structure with two legs are the Asimo of Honda, Japan [3], Johnnie developed at the TU Munich, Germany [4] and BARt-UH of the University Hanover, Germany [5].

The CENTAUROB is a statically stable walking biped robot. His structure is modular and consists of two Stewart-Platforms with a C-like foot shape and a mass displacement system. Taking this system as basis we found a large variety of static stable systems by making intentional changes in the robots structure. The procedure of intended changes is used to receive variations of a given solution. This method very often delivers solutions for areas of application that were never thought of in the first place.

The project itself was divided into three levels:

- In the first level a function model of static stable walking had to be created. Based on this prototype we studied the basics of static stable walking.
- In the second level we reengineer the mechanical structure and add advanced functions to the robot. He learns to sense his surroundings and how to react on his environment. At the moment we test and optimise this robot on a new test area.
- In the third and last level, we want to add a complete sensor system to the robot and teach him to fulfil some simple tasks.

The initial project level was successfully completed at the University of Paderborn in 2000 [1; 2]. Today, the work on the CENTAUROB is continued at the Hamburg University of Technology. A team of research assistants and several students has joint forces to push the ongoing project. We also established connections to other institutes of the university in order to incorporate additional expert knowledge in the field of software and hardware design and control theory.

Our vision is to create a mobile robot which can operate autonomously and fulfil various tasks from housekeeping to inspection of contaminated environments. This implies the use of an independent power supply, a stand-alone control system and compliance to essential safety requirements in human surroundings. For this reason, the CENTAUROB underwent a complete redesign from the basic function model which is set up in a defined laboratory environment to a new advanced prototype that can adapt to his surroundings. Every mechanical component was reviewed in order to reduce weight, increase dynamics and efficiency of the moving mechanism. The control system had to be completely changed, from path planning and step primitives down to the closed-loop control of the single actuators.

In this article we will present the new developments that have been achieved in the second design level and continuative aims. Figure 1 gives an overview on the structure CENTAUROB and the current research areas.

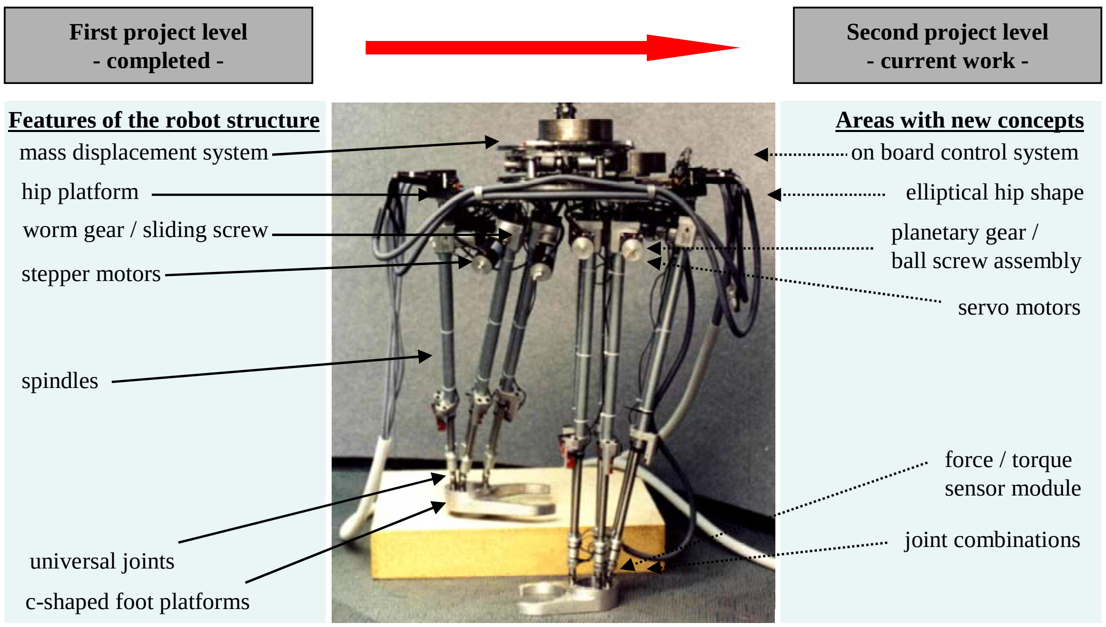

Figure 1: The CENTAUROB project

Kinematical structure

Locomotion is a crucial factor in the development of humanoid robots. Especially when an unstructured terrain including barriers has to be crossed, many robots that are in use today reach their limitations. The CENTAUROB uses two Steward-platforms as kinematical structures for the legs. By this means, the advantages of parallel kinematical structures can be used. This comprises high load capacity, dynamics, precision and stiffness. Moreover, the telescopic motion of the legs gives a simple and comprehensive ability to handle high steps, stairs or low clearances. The 6 degrees of freedom of each foot allow the adjustment to many surfaces. This moving technique of the CENTAUROB is a major breakthrough in technology and is a base for further engineering. A wide field of possible areas of action is opened, because no special environment has to be prepared to enable it to move without problems. The C shaped feet, which are protected by patent rights [1] allow the robot to move in very narrow rooms (which was one of the essential development goals) while always remain in a statically stable state.

Analysis and optimization of the Stewart-platforms architecture

The two Steward-platforms are attached to the hip platform with their circular base platforms side by side. At present, this results in a lateral dimension which is explicitly wider than a human hip. The width of the hip determines the flexibility of the robot as it limits the opportunity to pass through narrow passages. That is why the effect of several design alternatives was evaluated. For this purpose, a mathematical description of the kinematical structure was developed in terms of a multibody system model which allowed evaluating resulting changes of different geometric parameters.

The analysis based on the model was carried out by varying hip platform size and shape, foot size, joint angles and joint positions. All kinematic and static properties were computed numerically over the dexterous workspace (Figure 2) and displayed in different slice planes. With the step height and step width two specific parameters were defined. Only a single Steward-platform was considered, with foot- and hip platforms described by their global position vector and rotational matrix respectively. A fixed position of the hip was chosen, remaining the set of independent variables represented by the global coordinates of the foot platform. The transformation between these coordinates and the actuator lengths is given by the inverse Jacobian matrix. Using the Jacobian matrix, the maximal velocities and forces and the stiffness could be determined.

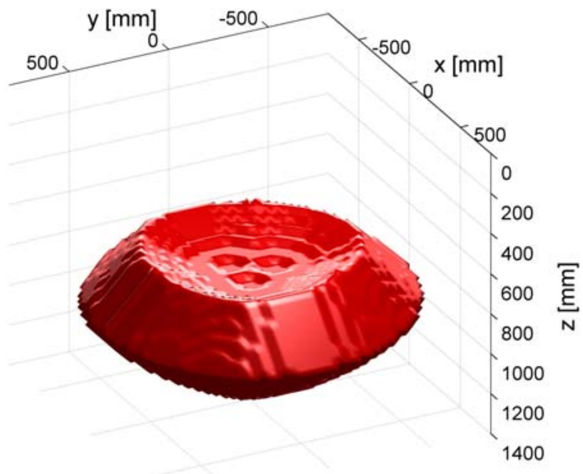

Figure 2: Workspace of a single foot in the first project level

The Steward-platforms are very slim and tall which is very unusual. This gives the legs a human-like appearance, but also draws the kinematical structure near a singular configuration. The actuators are primarily aligned in the vertical direction which gives a high load capacity and tributes to the gravitational loads. However, the CENTAUROB moves mostly forward, almost perpendicular to the single actuator alignment. Resulting, the maximum forces and rigidity in the horizontal plane are considerably lower than in the vertical direction. Tasks that require additional pulling or pushing forces in horizontal directions will be critical for determination of the CENTAUROB's performance envelope.

The analysis led to a set of design guidelines for our special mechanism. Important aspects that are respected by these guideline are step height and width, workspace, forces, stiffness and singular configurations, where unwanted degrees of freedom occur.

It could be shown that hip dimension and shape have a consequential influence on all kinematical and static parameters. Using a small hip platform diameter leads to a consequent degradation of the performance. See the dependence of the maximal horizontal force at the foot platform with respect to the hip radius as shown in Figure 3.

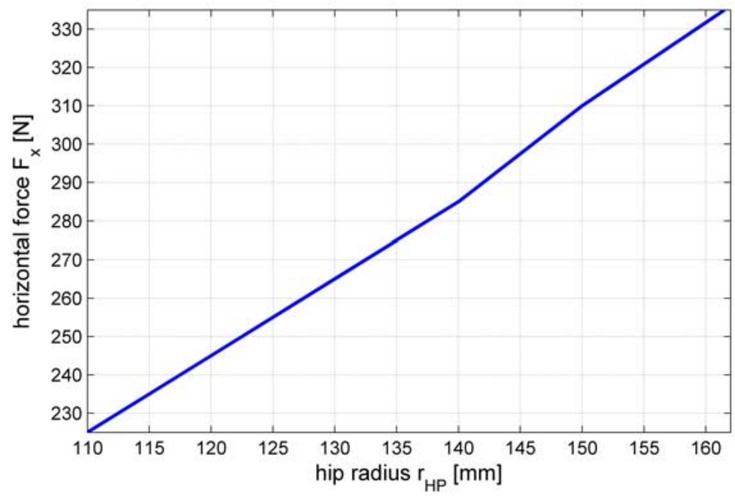

Figure 3: Maximal horizontal force F_x vs. hip radius r_{HP}

The question was to find the optimal solution for the rivalling aims package space reduction and mechanical performance. Our idea was to see each direction of motion independently. The circular shape of the hip can be replaced by an elliptical shape with a smaller diameter only in the lateral direction. By this means, the good performance in the dominant forward direction can be preserved in combination with a narrow hip size.

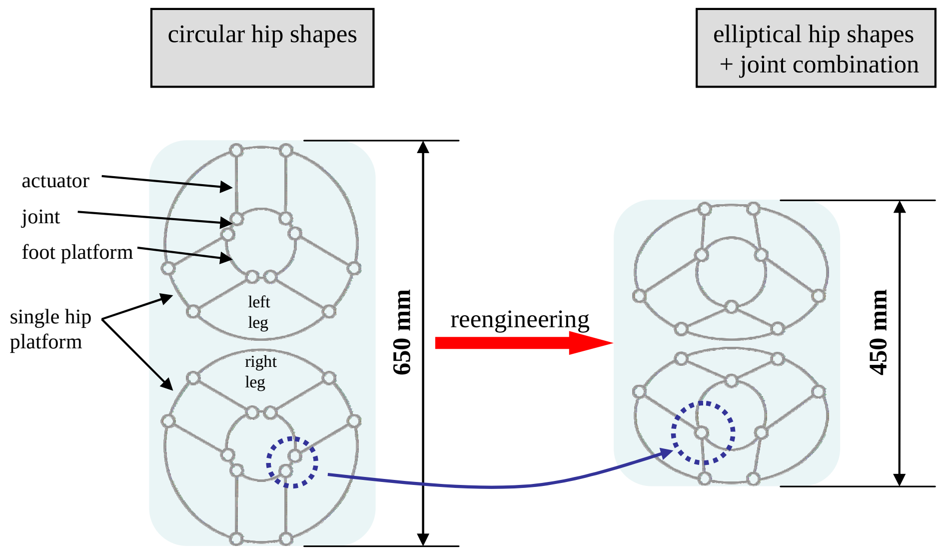

Figure 4: Modification of hip shape and joints

Another result was that the joints on hip and feet should be grouped in pairs with an offset of 120° between the pairs and 60° between the platforms in order to reduce the possibility of singular configuration and increase rigidity. Moreover, the maximal moving angle of each joint has an impact on the workspace volume. Eventually, an elliptical shape of the hip platform was chosen in combination with the integration of two joints in a special joint with increased flexibility and stiffness at the foot (Figure 4). Pairing of joints at the hip is not possible due to the required space for motors and transmission gears.

Mechanical components

The intensive research has lead to the first prototype, which is able to move forward and both sides or overcome up to 500 mm obstacles or steps. This prototype was build mainly from standard parts regarding joints and actuators.

In the second design level the review of every single mechanical component lead to the conception of a complete redesign which includes the following features:

- High performance electronically commuted servomotors (250 W / 48 Volts) will replace the formerly used stepper motors.
- The active joints lengths are measured with absolute value sensors. This will reduce efforts for calibration and eliminate tracking of reference points.
- A new six-component force sensor module will be integrated in the foot platforms. By this means contact forces and moments which arise from ground contact or unwanted collisions can be detected.
- Friction reduced ball screw assemblies and planetary gears replaced the inefficient sliding screw and worm gear at the transmission between motor and spindle. Since the new mechanism is not self-locking, a brake is required for safety reasons in case of a power or control failure.
- The active and passive joints are optimized regarding rigidity and clearances in order to reduce position errors.
- According to the optimization results for the mechanism, two standard universal joints between actuators and foot platform are replaced by one combined 3-DOF joint.
- The hip platform is reengineered by applying lightweight design methods and materials. Critical loads are identified and reduced by optimizing the structure with FEM.

We obtained the usage of many recurred parts for the legs to reduce manufacturing costs and minimize the number of spare parts that have to be kept in stock.

Control system

In the first project level, the main propose of the prototype was to determine the basic abilities of the CENTAUROB and to develop a walking pattern concept based on a feed forward control schema using previously calculated step primitives. Computations were carried out by several external computers. Now, we concentrate on the development of a much more sophisticated closed-loop control system accompanied by using a significantly extended sensor structure. Every single servomotor can be controlled by a cascaded current-, velocity- and position-control using decentralized control structures, which is very common in parallel kinematic control. Another promising control concept could be developed with loop-shaping methods like Glover-McFarlane and sensitivity shaping using a MIMO plant of the whole hexapod instead of parallel SISO plants of the single actuators [10].

Since the CENTAUROB shall operate autonomously, the control device has to be integrated in the robots structure. The aim is to establish a real-time control that allows the online computation of the complete robot motion with respect to his environment. Fortunately, the structure of each leg with its single actuators is identical, making at least the calculation of the inverse kinematics easier to solve.

The performance of every control system depends on the quality of the underlying model of the plant. For this reason, we are evaluating a complex multibody-system model of the Steward-platforms [7; 8]. Competing robots systems often suffer from oscillations in the motions and peak overshoot at the end points of commanded position changes. Especially the low stiffness in the horizontal plane is responsible for this behaviour. A precise real-time computation of dynamic forces might solve this problem.

Biped walking control

The biped balance control strategy for the CENTAUROB can be divided by different levels of abstraction, dimension of plant models and calculation routines [9]. A shared feature is the calculation of the centre of mass (COM) and the zero moment point (ZMP) [6]. These geometric parameters define the stability for static and dynamic motion. Figure 5 shows a process diagram with possible paths to realise stable walking.

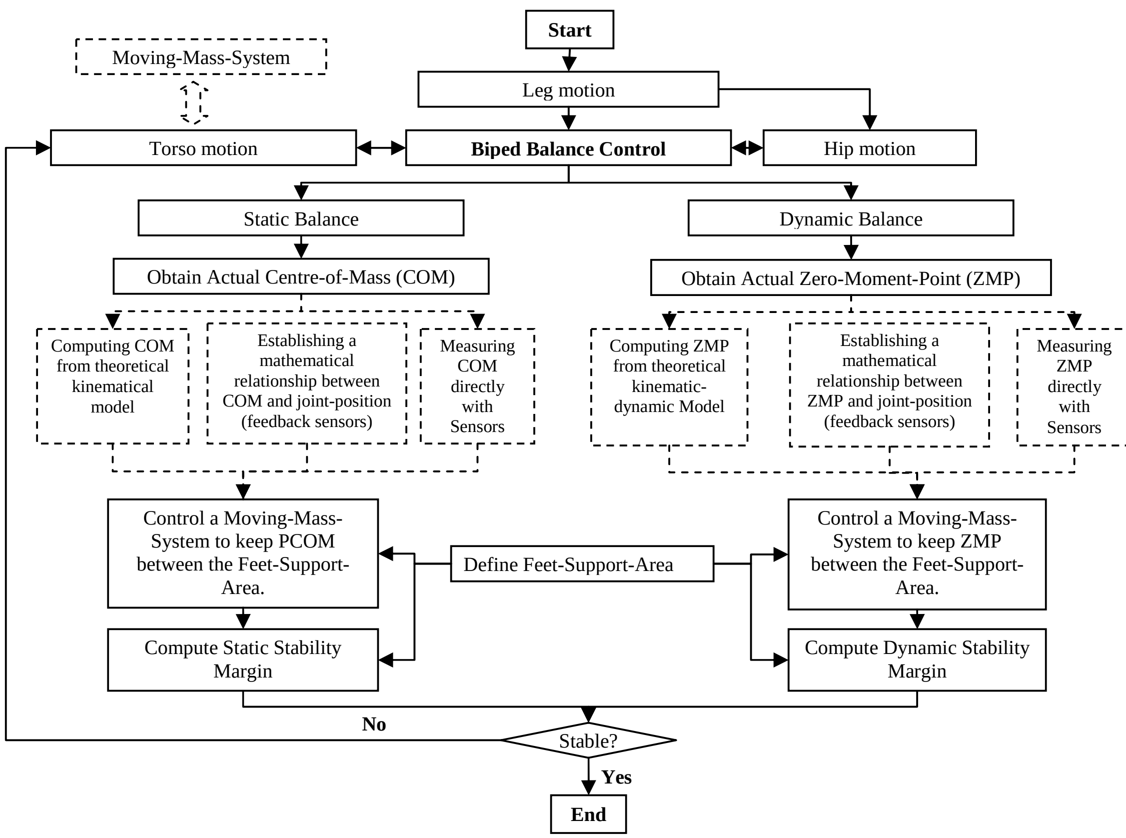

Figure 5: Biped balance control strategy

In the first design level a trajectory database concept was established, where a database of optimal trajectories was generated considering walking phase, ground shape and other influences. A sequence of step primitives is then selected from the database to pursue on a commanded path.

While this method works very efficiently regarding computation demands, the missing incorporation of environmental data makes it insufficient for an autonomous robot. For this reason, an additional real-time control with feedback loops from various sensors will be implemented. The sensor data will comprise position, translational and rotational acceleration, forces and moments and visual information. By these means, centre of mass and zero moment point will be calculated continuously in order to remain in a stable state and to observe the compliance to commanded motions. The degree of stability of the robot can be measured by computing a stability margin, which is the shortest distance between the COM or ZMP of the robot and the bounding of the support area formed by the convex hull of the feet support area.

Trajectory generation method

The first step in walking trajectory generation is to plan the swing-foot trajectory based on the obstacle information. Once the swing-foot motion is fixed, a hip trajectory can be determined taking into consideration the stability imbalances caused by the foot motion. Given the swing-foot and corresponding hip trajectories, the joint trajectories can be computed using the inverse kinematics. The calculation of the inverse kinematics of the swing-foot is carried out using a local coordinate system fixed at the hip, while the calculation for the support foot is carried out based on the fixed inertial coordinate system, whose origin is in the centre of the support-foot joint positions. The absolute trajectory of the swing foot is the vector sum of the hip trajectory and the swing foot-trajectory relative to the hip. From the inverse kinematics and dynamics of the feet platforms, positions, velocity, and acceleration of each link, as well as the forces acting at the links can be determined. The possibility to implement the generated trajectories can be tested by comparing the positions, velocities, and forces at the joints with that of actuator specification.

The trajectories are divided in several sections and approximated with fifth-order polynomials. Lengths of the sections can be determined by extension of obstacles or other discontinuous changes in the ground geometry. The fifth-order polynomial approximation was selected because it can guarantee continuity of accelerations during transition between the different sections. Figure 6 shows a typical trajectory for the foot as it moves forward to a new commanded position.

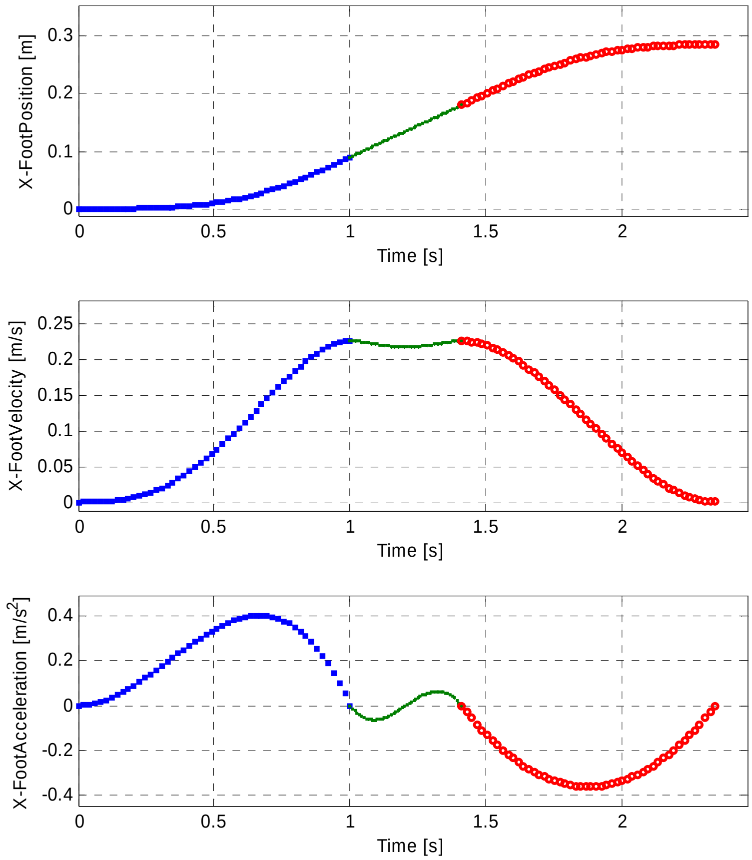

Figure 6: Fifth-order polynomial trajectory for forward foot motion

Virtual test environment

Since the extensive evaluation of the actual prototype requires a lot of time and manpower, we are using an additional virtual prototype. By employing a co-simulation of a multibody-system software and a widely used controller design software we can test the performance and control schemes online even before the completion of the new prototype. Moreover, control system and hardware can be evaluated independently using state of the art "hardware-in-the-loop" methods.

Conclusion and outlook

The ongoing development of the CENTAUROB has reached the next level. With the new prototype the performance regarding mechanics and control will be significantly increased. This is due to a comprehensive reengineering incorporating optimization of the mechanical structure and components, lightweight construction, and application of FEM. It was shown how the evaluation of several geometric parameter variations led to the design of a new hip shape and joint configurations. Additional sensors and integrated sensor modules will be used to establish a closed-loop control system. The extension from a trajectory database concept to a real-time motion control was described, which uses polynomial approximations of trajectory sections.

The ongoing evolution of autonomous service robots is evidently and leading to the development of many elaborated concepts. The creation of artificial intelligent beings and the interdisciplinary character of the project are very attractive, which is shown by the high interest among industrial companies as well as many students, especially from mechatronical and mechanical engineering courses. For this reason we are very encouraged and ambitious to complete the next project level and to lead the CENTAUROB further to its maturity phase.

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