Darmstadt Dribblers 2004: Humanoid Robot

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Abstract. This paper describes the design and implementation of the first humanoid robot prototype of the Darmstadt Dribblers, which participated in the Humanoid League of RoboCup for the first time in 2004. The robot is used as a vehicle for research in control of locomotion and behavior of humanoid robots with many degrees of freedom and many actuated joints. For humanoid robots highly nonlinear physical dynamical effects must be considered on all levels of a reactive-deliberative control architecture realizing autonomous robot behaviour. The Humanoid League of RoboCup provides an ideal testbed as the problem of generating and maintaining statically or dynamically stable bipedal locomotion is predominant for all types of motions during a soccer game. The team has evolved from the Darmstadt Dribbling Dackels team which continuously has participated as part of the German Team in the Sony Four-Legged League since 2001.

1 RoboCup and the Dynamics of Robot Motion

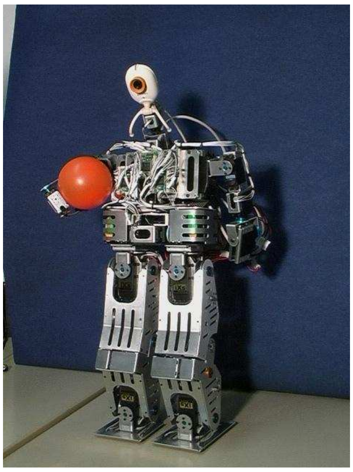
The RoboCup scenario of soccer playing legged robots represents an extraordinary challenge for the design, control and stability of bipedal and quadrupedal robots. In a game, fast motions must be planned autonomously and implemented online which preserve the robot's stability and can be adapted in real-time to the quickly changing enviroment. Existing design and control strategies for humanoid robots can only meet these challenges to a small extent.

During the nineties, both trajectory planning methods relying on nonlinear robot dynamics and model-based control methods have evolved into the state-of-the-art for developing and implementing fast and accurate motions for industrial manipulators. Successful control of the nonlinear robot dynamics is also the key to fast and stable motions of bipedal and quadrupedal robots. Many subproblems remain unsolved in fulfilling this objective. The purpose of the Darmstadt Dribblers is to contribute to this ambitious goal by discussing fundamental principles and recent methods in the modeling, simulation, optimization and control of legged robot dynamics.

For wheeled robots in the Small and Midsize Leagues maintaining balance during locomotion is not a big issue. Thus, there is no need for using a kinetical model of wheel robot dynamics besides planning and implementing motions of high speed and high position accuracy. In the Four-Legged League mostly trot-like gaits on the elbows of the front legs are used. This results in a relatively low height of the center of mass above ground, and thus, maintaining balance is not too difficult. However, in the Humanoid League the problem of stability of legged locomotion cannot be avoided.

2 Technical Data of the Humanoid Robot Prototype

The humanoid robot we use in RoboCup 2004 is depicted in Fig. 1 (as in February 2004). The robot is a unique prototype which has been custom-made for our purposes by iXs Research Corporation (http://www.ixs.co.jp).



height:	60 cm
width:	31 cm
weight:	4.8 kg
degrees of freedom:	24 in total with 6 in each leg, 4 in each arm 2 in waist, 2 in neck
sensors:	3 force sensors in each foot, 24 joint angle encoders, 1 camera (Philips, ToUCam, resolution: 640 x 480, 60 fps)
control frequency	2 ms
processor:	NEC Vr4181A 133 MHz
operating system:	Linux
network:	Wireless LAN, LAN
power supply:	onboard batteries

Fig. 1. Appearance and technical data of humanoid robot prototype.

3 Efficient Dynamic Modeling of Biped Locomotion

Nonlinear Dynamics of Legged Robot Motion A precise modeling of fast moving legged locomotion systems requires high dimensional nonlinear multibody dynamics which can accurately describe the nonlinear relationships existing between all linear and rotational forces acting at each joint and the feet on the one hand and the position, velocity and acceleration of each link in the kinematic tree-structure on the other hand. It is thus a complex task to generate and control stable motions for such systems. Biped and quadruped constructions generally consist of a minimum of five bodies with two to six degrees of freedom (DoF) per leg in addition to the six DoF corresponding to the base body in order to give the necessary amount of motion dexterity necessary for a wide range of movement. Dynamic model simplifications in previous work, however, have generally ranged from pendulum models to multi-link planar models for bipeds and for quadrupeds or to multi-link spatial models [8, 9]. Though these simplifications allow one to analyze certain predominant behaviors of the dynamic system, many other important features are lost. A complete and complex dynamical system description will contain much more of the significant dynamical effects, yet a control solution for these models based on an analytical approach is usually not possible and results must be sought for numerically.

The dynamic effects characterizing bipedal and quadrupedal motion may be further complicated by external disturbance factors and forces, quickly changing system goals, low friction conditions, a limited power source, and inexact sensor information resulting from fast movements and a highly dynamic environment. These are all characteristics of the difficulties encountered in the Four-Legged and Humanoid Leagues of the RoboCup soccer challenge.

Dynamic Model Our basic model of the humanoid consists of a 7-link tree-structured multibody system (MBS) with a central torso attached and two three-link legs. A minimum set of coordinates consists of 18 position and 18 velocity states $(\mathbf{q}(t), \dot{\mathbf{q}}(t))$ which include a three-parameter Euler angle vector for the orientation, a three-dimensional global position vector, and their time derivatives for the torso, and additionally six angles and their velocities for each leg. The 12 control variables $\mathbf{u}(t)$ correspond to the applied torques in the legs. The motion of the arms and the upper body and the corresponding actuated joints are not considered in this basic model but will be considered in a model upgrade as the coordinated, contralateral swinging motion of arms and legs during walking stabilizes bipedal locomotion.

Solutions for Multibody Dynamics of Legged Robot Models. Multibody dynamical models for real legged systems are typically characterized by a high number of DoF, relatively few contact constraints or collision events, and a variety of potential ground contact models, actuator models, and mass-inertial parameter settings due to changing load conditions. Such detailed multibody dynamical models are generally required for the realistic reproduction of legged system behavior in gait optimization, tuning of construction design parameters or in simulation and feedback control [8, 9]. Closed-form dynamical expressions are the most efficient form of evaluating the dynamics, but are not well-suited to legged systems due to the many changing kinematic and kinetic parameters. Recursive, numerical algorithms are also highly efficient for large systems and permit the easy interchangeability of parameters and the introduction of external forces without repeated extensive preprocessing. This approach has been used here. Reduced dynamical approaches appropriate for legged robots are additionally presented.

Articulated Body Algorithm Various approaches exist for dealing with multibody systems' equations. We chose articulated body algorithm (ABA) due to its several advantages over other methods like symbolic methods, composite rigid body algorithms or natural coordinates. ABA is a numerical, recursive, order N algorithm (where N is the number of links in the multibody system). It shows a high modularity with respect to exchange of submodels within the dynamic structure, useful when considering different actuators or limb complexity, and varying contact situations of different feet having contact with ground. It is useful to be able to work with the same model, even if parts of the model are substituted by improved models. Also a model that may be used in all different situation when considering the robot is desired: ABA may be used in off-line trajectory calculation, estimation of parameters in the model and model-based on-line controllers as well.

The basic equations of motion are those for a rigid, multibody system experiencing contact forces

$$\begin{aligned} \ddot{\mathbf{q}} &= \mathcal{M}(\mathbf{q})^{-1}\Big(B\mathbf{u} - \mathcal{C}(\mathbf{q},\dot{\mathbf{q}}) - \mathcal{G}(\mathbf{q}) + J_c(\mathbf{q})^T \mathbf{f}_c\Big) \\ 0 &= \mathbf{g}_c(\mathbf{q}) \end{aligned} \tag{1}$$

where N equals the number of links in the system, m equals the number of actively controlled joints, $\mathcal{M} \in \mathbb{R}^{N\times N}$ is the square, positive-definite mass-inertia matrix, $\mathcal{C} \in \mathbb{R}^N$ contains the Coriolis and centrifugal forces, $\mathcal{G} \in \mathbb{R}^N$ the gravitational forces, and $\mathbf{u}(t) \in \mathbb{R}^m$ are the control input functions which are mapped with the constant matrix $B \in \mathbb{R}^{N\times m}$ to the actively controlled joints. The ground contact constraints $\mathbf{g}_c \in \mathbb{R}^{n_c}$ represent holonomic constraints on the system from which the constraint Jacobian may be obtained $J_c = \frac{\partial \mathbf{g}_c}{\partial \mathbf{q}} \in \mathbb{R}^{n_c\times N}$, while $\mathbf{f}_c \in \mathbb{R}^{n_c}$ is the ground constraint force. $\mathbf{q}$, $\dot{\mathbf{q}}$, and $\ddot{\mathbf{q}}$ are the generalized position, velocity and acceleration vectors respectively.

The articulated body algorithm exploits the tree structure of the multibody system by calculating dynamics in several sweeps from base to tip and tip to base. Three sweeps are needed for evaluating forward dynamics, two additional sweeps treat contact situations. The transfer operators from one link to the subsequent resp. preceding link have equivalents in Kalman Filter theory, making the algorithm interesting from a mathematical point of view. Details may be found in [5]. We use the implementation SOAFOR (Spatial Operator Algebra Fortran routines [5]) of the articulated body algorithm.

Reduced Dynamics Algorithm The numerical difficulties associated with the system of differential algebraic equations of high index, resulting from the general modeling approach of multibody dynamics and algebraic equations for contact, can be avoided. This is done by a reduced dynamics method, treating explicitly only the independent states $\mathbf{q}_I$, which are global orientation and position and states related to legs in contact with ground, and using inverse kinematics to determine the dependent states $\mathbf{q}_D$ of the other legs:

$$\begin{aligned} \mathbf{q}_I &:= \text{global orientation, position; swing leg(s) states} \\ \mathbf{q}_D &:= \text{contact leg(s) states} \end{aligned}$$

$\mathbf{q}_I$ may be computed from all states $\mathbf{q}$ using a constant mapping Z, i.e. $\mathbf{q}_I = Z\mathbf{q}$. The solution of the reduced dynamics

$$\ddot{\mathbf{q}}_I = Z\mathcal{M}\left(\tilde{\mathbf{q}}\right)^{-1}\left(B\mathbf{u} - \mathcal{C}\left(\tilde{\mathbf{q}},\dot{\tilde{\mathbf{q}}}\right) - \mathcal{G}\left(\tilde{\mathbf{q}}\right) + J_c^T \mathbf{f}_c\right),$$

where $\tilde{\mathbf{q}}$ consists of the independent states and of the dependent states determined from inverse kinematics, then may be proven to be the solution of the initial system of differential algebraic equations (1) [5]. Inverse kinematics for each leg of the robot here has a unique solution if agreements concerning the bending of joints are made. This makes it possible to deal with reduced dynamics algorithms. As a result, 24 instead of 36 states can describe the model and a set of ordinary differential equations only instead of a system of differential algebraic equations may be considered.

4 Obtaining Stable Locomotion by Dynamic Trajectory Optimization

Dynamical Stability of Legged Robot Motion There exists a wide spectrum of previously presented approaches for generating dynamically stable motions in bipeds and quadrupeds. Analytical methods usually rely on simplified models like inverted pendulums and are not yet at a stage where the many influencing dynamical effects previously mentioned can be considered. More complete 3-D modeling approaches for bipeds generally rely on heuristic schemes to construct dynamically stable motions. The dynamic stability criterion is usually based on the Zero-Moment-Point yet this criterion is limited in its ability to classify stability during, for example, periods of rolling motion of the feet, which for fast-moving systems can be considerable. In the case of quadrupeds with point contacts, a similar problem occurs. Such gait planning techniques also rarely consider the stabilizing potential of the torso sway motion or that of arm swinging which can be advantageous for increasing robustness and reducing power consumption. Nonetheless, 3-D bipeds and quadrupeds have been constructed which perform dynamically stable walking and running. Though due to excessive power consumption they were either not autonomous or required a substantial battery supply for only a short operational period. In our research, alternative stability as well as energy-based performance measures suited for bipedal and quadrupedal gait generation are investigated.

Generating dynamically stable symmetric gaits for legged robots is still a challenge. Landing time and point of each leg are prescribed, i.e. they depend on parameters. The trajectory of each joint between lift-off and landing is not uniquely determined. To overcome this problem of redundancy, the problem of finding a dynamically stable symmetric gait is formulated as an optimal control problem, involving the robot's dynamics and several additional constraints. Efficient methods are needed for both the dynamics and the resulting optimal control problem. The resulting trajectories are implemented on the robot using the given trajectory tracking control on joint level. Therefore, the optimal control problem formulation for the computation of reference trajectories for a dynamic gait must account for possible inaccuracies in the dynamic model and parameters as well as for external disturbances. All aspects of generating a reference trajectory by dynamic optimization, that can be implemented on the real robot, are presented in this section.

Numerical Optimization and Feedback Control of Bipedal and Quadrupedal Robot Motions. Algebraic control strategies for legged systems cannot yet handle the high dimension and many modeling constraints present in the locomotion problem. Heuristic control methods, on the other hand, tend to have poor performance with respect to power efficiency and stability and require much hand-tuning to acquire an acceptable implementation in a fast-moving legged system. The remaining proven approach is the use of sophisticated numerical optimization schemes to generate optimal trajectories subject to the numerous modeling constraints. The resulting trajectories may later be tracked or used to approximate a feedback controller in the portion of state space of interest.

In our efforts to achieve dynamically stable and efficient gaits for the Sony RoboCup quadruped [12] and the humanoid robot protoype under joint development with the Control Systems group of TU Berlin [2, 10] we explored a numerical optimization approach which minimize performance or stability objectives in the gait generation problem. Numerical optimization tools have advanced sufficiently [4, 13] such that all the above-mentioned modeling and stability constraints can be incorporated into the problem formulation together with a relatively complete dynamical model so as to obtain truly realistic energy-efficient, stable and fast motions.

Optimal Control Problem The problem of finding a symmetric gait for the humanoid robot is stated as an optimal control problem with several phases. During one phase contact situation may not change for sake of having to deal with a well defined set of considered states (states related to legs with feet in contact with ground are not considered when using the reduced dynamics approach). Since for other movements than walking only the boundary and nonlinear inequality constraints have to be changed, the following shall stand as an example for more general movements like shooting a ball.

The optimal control problem is stated as follows:

$$
\begin{array}{cl}
\min \mathcal{J}[\mathbf{q}, \dot{\mathbf{q}}, \mathbf{u}, t_f] \ \text{ subject to} & \text{minimize the merit function } \mathcal{J} \text{ subject to} \\
\mathcal{M}\ddot{\mathbf{q}} = B\mathbf{u} - \mathcal{C}(\mathbf{q}, \dot{\mathbf{q}}) - \mathcal{G}(\mathbf{q}) + J_c^T \mathbf{f}_c, & \text{system of MBS ODE} \\
\mathbf{g}_c(\mathbf{q}) = 0 & \text{contact algebraic conditions} \\
\mathbf{b}(\mathbf{q}(t_0), \mathbf{q}(t_f), t_0, t_f) = 0 & \text{boundary conditions} \\
\mathbf{n}(\mathbf{q}, \mathbf{u}) \geq 0 & \text{nonlinear inequality constraints,} \\
\mathbf{q}_{\min} \leq \mathbf{q} \leq \mathbf{q}_{\max}, \ \ \mathbf{u}_{\min} \leq \mathbf{u} \leq \mathbf{u}_{\max} & \text{box constraints on state and control variables.}
\end{array}
$$

Note that the optimal control problem in this notation contains the differential algebraic equation of multibody system differential equations and contact algebraic equations. However, when solving the optimal control problem, this system of differential algebraic equations can be replaced by the reduced dynamics equations.

Useful merit functions are, for example, time t_f, energy $\int \sum_{i=1}^{m} u_i^2$, or combinations of both [9]. Boundary conditions contain conditions for

- symmetry resp. anti-symmetry of states,
- foot placement, i.e. conditions that force the feet to be placed on desired positions (which may depend on parameters and therefore may also be subject to the optimization),
- contact forces at the end of a stance phase, that allow the foot to lift off.

Nonlinear inequality constraints are:

- Hips of legs in contact with the ground must stay within a maximum radius of the leg, so that the inverse kinematics solution required for reduced dynamics has a well-defined solution.
- The swing foot must move above a certain curve above ground, for example a proper sine curve. This property increases stability by avoiding contact with the ground resulting from deflexions of bodies and joints, and which could lead to stumbling of the robot.

– Slipping is avoided by limiting the horizontal contact forces relative to the vertical contact forces.
– Vertical contact forces must be positive, i.e. the robot may only push to ground but may not pull from ground.
– Further constraints to be considered in the problem formulation are detailed motor characteristics. By now the box constraints for minimal and maximal values of angular velocities and torques only give a rough estimate of the real actuator data.

Note that stability is not enforced explicitly, while of course implicitly it is ensured by periodicity of the generated gait and may be checked by one of the criteria given in [9]. More details on each of the constraints may be found in [2], where the constraints are stated explicitly.

Solving the Optimal Control Problem For solving the optimal control problem, the method DIRCOL [13] is used. The states and controls are approximated by piecewise cubic resp. piecewise linear polynomials on a discrete and successively refinable time grid. The optimal control problem is thereby transcribed into a nonlinear program with the coefficients of the polynomials as variables, which may be solved by a sequential quadratic and, due to the special structure of the variables, sparse programming method [4]. For more details we refer to [6, 13].

It is worth to mention that the approach presented in this section has not only aided in the design of a humanoid robot prototype [14] but also enabled this prototype to walk stable without measuring ground reaction forces or accelerations of the upper body and using only PID joint control of the optimized trajectory [2].

5 Autonomy of the Robot

So far autonomous capapilities of the most successful walking, humanoid robots (like Honda Asimo or Johnnie of TU München) are restricted mainly to locomotion, e.g., walking without loosing balance and vision-based navigation which represent quite difficult tasks on their own. However, locomotion and navigation are the most fundamental, autonomous capabilities required by a mobile, autonomous robotic system. For realizing further, autonomous capabilities enabling the humanoid robot to solve complex tasks the development of a complex, deliberative (for solving complex tasks through planning), reactive (for quickly reacting on new sensor data) or hybrid, reactive-deliberative control architecture is needed. Our vision is to develop a modular, object oriented control architecture which accounts for the predominant influence of motion dynamics of the humanoid robot in all aspects of planning of deliberative or reactive robot controls.

As a starting point we consider the modular, object oriented software architecture developed within the German Team for the Sony Four-Legged League [11]. The architecture enables the development and testing of different, alternative modules for sensor processing, object recognition, object modeling, behvior control, and motion control. Like the Sony robot our humanoid robot protoype has a single CCD camera on the head to search the environment for objects of special interest, e.g., a ball or colored obstacles. In addition to the position encoders in each actuated rotational joint there are three force sensors in each foot to measure ground reaction forces for maintaining balance while walking around the field or kicking the ball.

Currently our robot's hardware enables autonomy with respect to motions based on joint angle or force sensors. However, it is not clear at this time, whether all the computations required for image processing and object recognition can be performed by the onboard processor or must be performed in parts or in total on a remote brain processor. For all online computations as well as for all actuated joints the onboard batteries provide enough power for autonomous operation during competitions.

6 Conclusion

This year is the first time that our team enters the Humanoid League. Our goal this year is to successfully participate in all competitions. This will allow us to evaluate the first steps in this humanoid project.

As next steps we plan to include further sensors as a gyroscope and an accelerometer in the upper body. By these sensors the position estimate of the upper body can be improved by using Kalman filtering. Postion and velocity of the upper body are needed for developing (nonlinear) controls based on a model of humanoid robot dynamics representing another step towards the envisoned humanoid robot control architecture.

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