Combining Key Frame Based Motion Design with Controlled Movement Execution

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Abstract. This article presents a novel approach for motion pattern generation for humanoid robots combining the intuitive specification via key frames and the robustness of a ZMP stability controller. Especially the execution of motions interacting with the robot's environment tends to result in very different stability behavior depending on the exact moment, position and force of interaction, thus providing problems for the classical replay of prerecorded motions. The proposed method is applied to several test cases including the design of kicking motions for humanoid soccer robots and evaluated in real world experiments which clearly show the benefit of the approach.

1 Introduction

As the field of robotics shifts to more complex tasks such as search and rescue or military operations, but also service and entertainment activities, robots themselves are becoming more autonomous and mobile. To fulfill tasks in the later two areas of application, robots must be capable of navigating in and interacting with environments made for humans, and of communicating with people in their natural ways. Those environments are particularly challenging for the movement of conventional wheeled autonomous robots. Normal stairs or small objects lying on the floor become insurmountable barriers. For these reasons the design of such robots tends to mimic human appearance in respect to body design, capability of gestures and facial expressions [1].

As a consequence humanoid robots are one of the major topics of robotics research and are believed to have high potential in future applications. Despite this, present humanoid robots have a substantial lack in mobility. The humanoid shaped form of a two-legged robot results in a relatively high center of mass (CoM) of the body while standing upright. As a result the stance of a humanoid robot is quite unstable, making it likely to tip over. Even basic tasks as walking on even ground without external disturbance are not a trivial challenge. Therefore stability is one of the central problems in this area at the moment, with research focusing mainly on the task of walking. The execution of interactions with the robot's environment represents an even more difficult task because of

J. Baltes et al. (Eds.): RoboCup 2009, LNAI 5949, pp. 58–68, 2010.

the necessary coordination of sensor input and actuator control for targeting and for keeping a stable posture.

This task is easier for a wheeled robot since because of its low CoM position it is less likely to fall over while executing movements designed to handle an object. Maintaining stability during the execution of similar tasks is not trivial for a humanoid robot. The unstable nature of its design makes it vulnerable to disturbances during motions such as lifting an object of unknown weight. The classic approach to motion design typically exploits the fact that most actions needed of a robot can be considered as sequences of motion primitives adding up to perform a certain interaction with its environment or being executed periodically in case of walking. Consequently the design consists of rigidly specifying these motion primitives or key frames and corresponding transition times. This results in a fixed motion sequence thereby making it impossible to adjust the movement online during execution.

While the specification of key frame motion provides an intuitive way of dealing with complex motions and adjusting them for specific looks or purposes, stability aspects are typically neglected but for the point that the resulting motion is stable on the reference robot used for the design. Differences between several robots of the same model or variances in interaction characteristics are normally handled by redesigning the motion for each case or trying to find a best fit that covers most cases. Therefore this static motion design approach appears to be ineligible for humanoid robots approaching the suggested tasks. Hence the proposed system extends the idea of key frame based motion design by controlled movement execution according to predefined stability criteria. This allows for a simplified specification process while differences between robots and deviations due to other reasons are compensated by the stability control.

The next section gives an overview of research on postural stability and related work. Then the proposed motion design and the control system applied to the executed motion are explained. Following this the system is evaluated using the experimental setup of a kicking motion. This application of the presented algorithm clearly shows the benefit of the control system.

2 Motion Generation and Stability

According to [2,3,4], the existing approaches to control the motions of walking robots can be divided into the following two categories:

Offline generation. A motion is designed before the execution resulting in the specification of a motion trajectory. The planned trajectory is executed once or periodically resulting in the desired motion.

Online generation. A motion is generated by a feedback control mechanism from a given motion objective in real time.

Offline motion generation has been applied since the beginning of robotics research. Teach-in techniques for industrial manipulators allow to design complex motions by manually moving the robot on a path leading to the desired motion during playback execution. The intuitive simplicity of this approach motivates the method of designing motions using key frames [5]. Different sets of joint positions are specified leading to key motion positions. The transition between these frames leads to motion fragments. Combined these motion primitives form the desired motions needed for application. Due to the high number of joints motions of humanoid robots are very difficult to design. Therefore the key frame procedure is particularly interesting for application in this field of robotics for its simple design of complex motions. As a downside the motion is executed without the possibility of online adaptation. So it is not possible to supervise and control the stability of movement execution rendering this approach unsuitable for tasks during which forces acting on the robot can change unpredictably.

Hence the concept class of online motion generation combines approaches capable of changing the planned motion during the execution which requires a method to generate a new trajectory movement. Normally a mathematical function and a model description of the robot is used to come up with a way to calculate the desired movement [2,3,4]. While finding a model or mathematical description of the desired movement is more complex than defining a key frame motion it offers the possibility to integrate feedback in the motion calculation and thereby adapt the motion to external influences. This advantage enables this kind of motion generation to use sensor feedback to supervise and control the stability of motions when unpredictable external forces act on the robot. Therefore a criteria to measure the stability of the robot is needed.

A robot's posture is called balanced and a gait is called statically stable, if the projection of the robot's center of mass to the ground lies within the convex hull of the foot support area (the support polygon). This kind of movement however covers only low speeds and momentums. Movements utilizing high joint torques and accelerations typically consist of phases in which the projection of the center of mass leaves the support polygon, but in which the dynamics and the momentum of the body are used to keep the gait stable. Those movements are called dynamically stable.

The concept of the zero moment point (ZMP) is useful for understanding dynamic stability and also for monitoring and controlling a walking robot [6,7]. The ZMP is the point on the ground where the tipping moment acting on the robot, due to gravity and inertia forces, equals zero. In the case of a quasi static motion this ZMP equals the ground projected CoM. Vukobratovic's classical ZMP notation [8] is only defined inside the support polygon. This coincides with the equivalence of this ZMP definition to the center of pressure (CoP) [9], which naturally is not defined outside the boundaries of the robot's foot. If the ZMP is at the support polygon's edge, any additional moment would cause the robot to rotate around that edge, i.e. to tip over. Nevertheless, applying the criteria of zero tipping moment results in a point outside the support polygon in this case. Such a point has been proposed as the foot rotation indicator (FRI) point [10] or the fictitious ZMP (FZMP) [8].

3 Motion Generation

In this paper a motion design concept is proposed which combines both methods discussed in section 2. Therefore a feedback controller is described in section 3.1, capable of controlling the CoM of a robot in a way satisfying the conditions of a quasi static motion. Section 3.2 describes the used key frame based feed forward control method, while section 3.3 describes the combination of both methods.

3.1 Quasi Static Feedback Controller

Motions such as manipulating objects normally require the robot to remain in position while moving only parts of its body resulting in rather slow joint movements. Hence a controller based on the assumption of a quasi static approximation is sufficient to control the motion.

At first the one dimensional problem of a center of mass R intended to reach the target position R' is considered. Without loss of generality $R' \geq R(0)$ is defined hereafter. To satisfy the condition of a quasi static motion, the acceleration must be bounded all the time.

$$|\ddot{R}(t)| \leq a_c$$

To generate the desired trajectory of the controlled motion the acceleration is set to its maximum value in the beginning and inverted once the target will be reached by maximal deceleration.

$$\ddot{R}(t) = \begin{cases} a_c & \text{if } t \in [0, t_1] \\ -a_c & \text{if } t \in [t_1, t_1 + t_2] \end{cases} .$$

To achieve this the remaining distance to the target must be covered during the time t_2,

$$-\frac{1}{2} a_c t_2^2 + \dot{R}(t_1) t_2 = R' - R(t_1) \tag{1}$$

and the velocity must be reduced to zero

$$-a_c t_2 + \dot{R}(t_1) = 0. \tag{2}$$

Elimination of t_2 out of equation 1 and 2 results in

$$\frac{1}{2} \frac{\dot{R}(t_1)^2}{a_c} = R' - R(t_1).$$

When this condition is met the acceleration is inverted. Therefore the acceleration is given by equation 3.

$$\ddot{R}(t) = \begin{cases} a_c & \text{if } \frac{1}{2} \frac{\dot{R}(t)^2}{a_c} < R' - R(t) \vee \dot{R}(t) < 0 \\ -a_c & \text{else} \end{cases} \tag{3}$$

The deviation between the measured and the desired CoM position and its current velocity is used as the system output and the acceleration of the CoM, calculated by equation 3, as the system input. The CoM position is computed by double integration as demonstrated in figure 1.

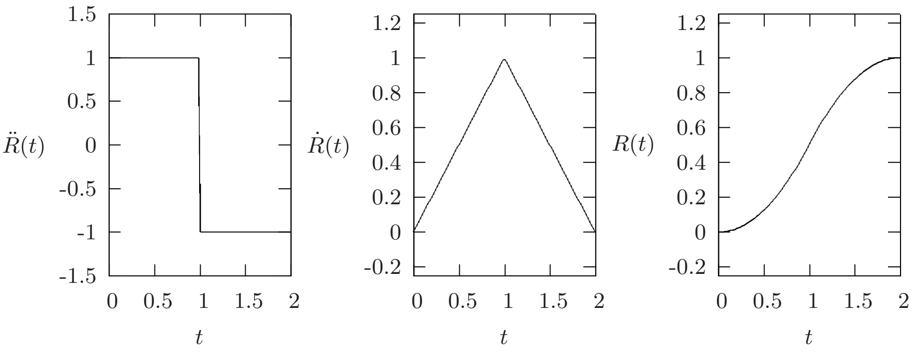


Fig. 1. Resulting position-, velocity- and acceleration curves for a quasi static controlled motion with $R(0) = 0$, $R' = 1$ and $a_c = 1$

To generalize the controller in two dimensions the control of the CoM motion is first considered to be independent and identical for both dimensions. The overall acceleration is hence bounded by the constant value $\sqrt{a_c^2 + a_c^2} = \sqrt{2}a_c$. With the target distances R_x and R_y being unequal in general the resulting movements tend to align along the axes as demonstrated in figure 2(a).

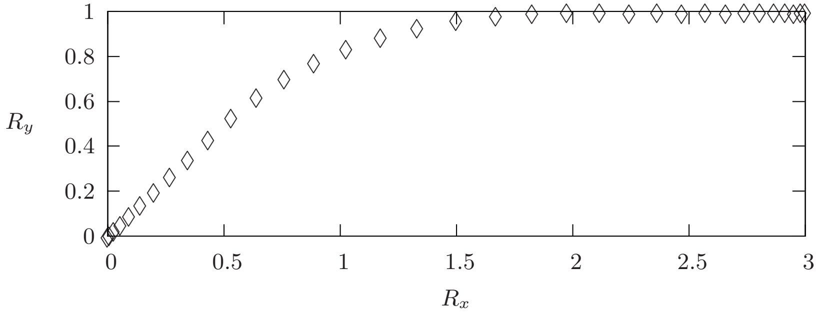
To solve this problem the coordinate system is transformed in every control step in such a way that one of its axes aligns to the current motion direction $\dot{\boldsymbol{R}}(t)$ and all calculations are done is the accompanying reference system of the CoM. As in the one dimensional case the acceleration in the orthogonal direction is used to reach the target position and the orthogonal acceleration turns the movement direction towards the target. The result can be seen in figure 2(b).

3.2 Key Frame Based Feed Forward Control

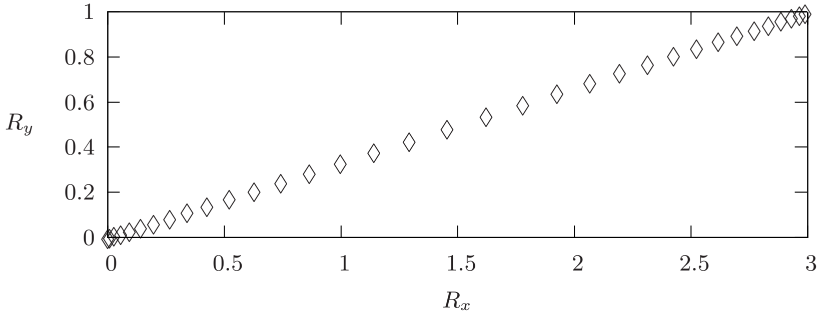
Similar to the approach used in [5] a key frame based motion is modeled as a list of positions. The motion is executed by interpolating between these positions within given times. In difference to [5] the proposed algorithm uses a notation in which a key frame is not defined directly by a set of joint angles but by defining the positions of the robot's body and feet in form of coordinates in the euclidean space. The according joint angles are computed by methods of inverse kinematics. The position of the feet are either given relative to the robot coordinate system or the position of one feet is given relative the other one. This definition not only results in a more intuitive movement specification, but also is more flexible in allowing degrees of freedom in the movement to be controlled during execution to match a desired criterium.

3.3 Combining Feed Forward and Feedback Control

As discussed in section 2 classic key frame based motions are unsuitable to be controlled to meat a stability criterion during execution due to the fact that



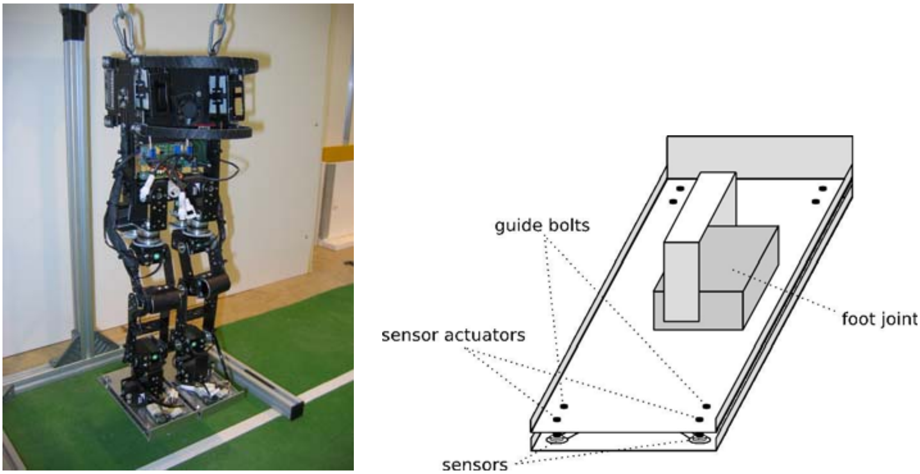
(a) original



(b) transformed

Fig. 2. Discrete two dimensional quasi static controlled motion with $R(0) = (0, 0)$, $R' = (3, 1)$ and $a_c = 1$

the movement of all joints is completely defined. Therefore in a novel approach both discussed methods are combined. The key frame based motion specification method discussed in 3.3 allows for a flexible motion definition without defining all degrees of freedom. While using this key frame approach to control the motion of the limbs, the orientation of the body in space, and the height of the CoM over the ground, the feedback controller presented in section 3.1 generates a motion trajectory for the horizontal components of the robot's CoM position ensuring the stability of the motion. As the desired stationary motions tend to require static stability keeping the ground projected CoM inside the robot's support polygon is sufficient to ensure this. Therefore a stable CoM trajectory is calculated in advance to match the specified motion. The fusion of the movements is then done by adding the resulting CoM position to each key frame. During motion execution the feedback controller ensures that the CoM follows the desired path by controlling the undefined degrees of freedom. The interpolation time associated to a key frame may not be equal to the time needed by the feed forward controller to reach the desired position in any case. Hence the transition from one key frame to the next can be delayed until the current CoM position is sufficiently close to the desired one and the current speed of the CoM is low enough.



(a) BHB-2 Bender (b) schematic sensor view

Fig. 3. Robotic platform used for experiments

4 Evaluation

To evaluate the concepts presented in this paper, experiments were conducted using a robot model of the type DHB-2 Bender (illustrated in figure 3(a)) which was designed and build by the *Dortmund University of Technology* and participated at the *German Open* and the *RoboCup* in the year 2007. In its current configuration it is 49 cm tall with a weight of 2.93 kg and a relatively high CoM of 31 cm. For more details see [11].

To measure the ZMP during the experiments the robot is equipped with sensors in the feet. Similar to the proposal of [8] four one axis force sensors of the type *FSR-149* (*International Electronics Engeneering)* are integrated into the corners of each foot as illustrated in figure 3(b). As stated in [8] the measured ZMP and thereby according to section 2, in the quasi static case, the projection of the CoM to the ground can be calculated by weighted summation of the sensor values.

To calculate joint angle values from the foot and body positions, a concept of inverse kinematics using the Newton method was applied [12]. To calculate the position of the CoM a simplified model consisting of three punctual masses, one for the body and one for each leg, is used.

4.1 Application to Kicking

To proof the concept of the controller described in section 3 a quasi static motion to stand on one leg and kick a ball is described in the following. This motion is chosen because kicking a ball is an easily repeatable motion which stresses the stability aspect in two ways: First, balancing on one leg might in itself be a difficult task depending on the rigidity of the leg design and the strength of the servo motors. In addition to that the exact moment, position and force of interaction with the ball is not known in advance which might cause additional instability if not countered correctly during runtime.

In the beginning of the motion the controller is used to bring the measured CoM position over the support foot. The other foot is lifted off the ground while the controller keeps the CoM over the support foot. During the actual kicking move the lifted foot is moved forward rapidly without altering the CoM position[1]. As this part of the movement only lasts for a very short time (about 100 ms) the relatively slow quasi static controller is not fast enough to adjust the movements of the robot during this phase. After the kick the feedback controller is used again to keep the CoM over the support foot leveling out the impact of the kick. For slower movements a CoM adjustment would also be possible during the motion execution. Since slower statical movements tent to be stable by themselves a demonstration is omitted at this point. The CoM is shifted back to its original position after the kick foot is moved to the ground. The direction of the kick can be controlled by turning the kicking foot around the vertical axis before performing the actual kick move while the range of the kick can be adjusted by modifying the speed of the foot motion.

Tests have shown that due to its too flexible leg structure the robot tends to bend into the direction of the lifted foot during the phases where it stands on one foot. This effect can be minimized, although not completely avoided, by tilting the robot's body into the direction of the standing foot before lifting the leg, as thereby the angle at the hip joint is less acute. The remaining instability is compensated by the controller.

4.2 Experiments

Figure 4 shows the motion of the robot's CoM during the tested kick movements. The diagrams show the y-component of the position of the center of mass relative to the center of the right foot. The dotted lines illustrate the position as it is set by the controller and the bold line shows the position as it is measured by the foot sensors.

In figure 4(a) the movement is done under the assumption that the input CoM position is the actual CoM position therefore without utilizing the actual feedback control. As can be seen the CoM is moved over the right foot at first. After about 5 s the robot starts to lift the left foot. As the robot is no longer supported by the left foot the right leg bends and the CoM moves to the left. Accordingly the figure shows a deviation of the measured CoM position to the left. The deviation is strong enough to make the robot topple over the left side of its foot and finally fall over.

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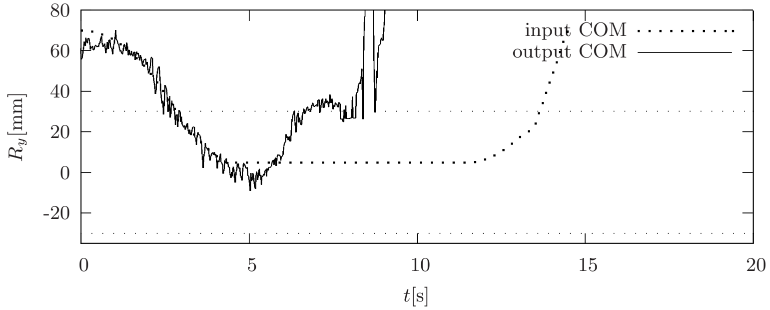
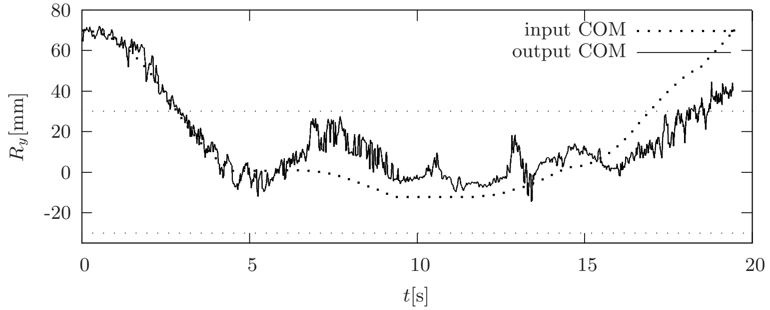
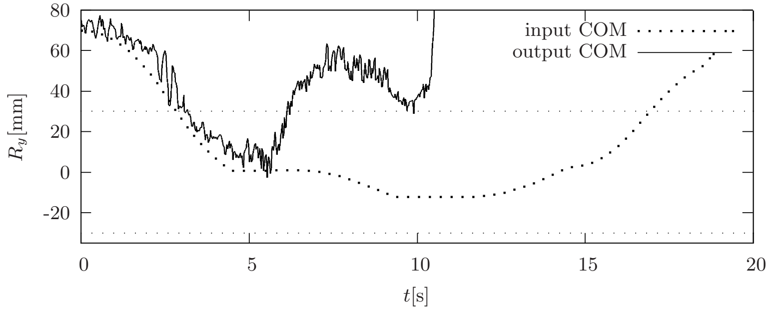
[1] This compensation of the CoM for the moving mass of the kicking leg is already inherent to the key frame specification if the CoM position is specified instead of the robot's coordinate system origin.



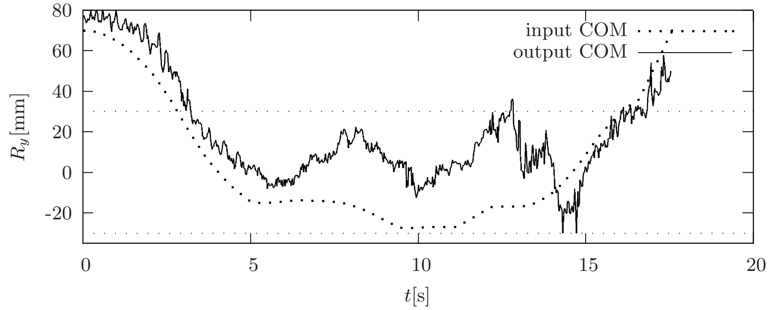
(a) undisturbed, without feedback



(b) undisturbed, with feedback



(c) disturbed, without feedback



(d) disturbed, without feedback

Fig. 4. Kicking motions using the quasi static controller without feedback

Figure 4(b) demonstrates the results of the movement utilizing the feedback control. As can be seen the controller reacts to the deviation of the CoM position by moving the CoM to the right side. So the robot is able to perform the actual kick move after about 10 s, lower the foot again and move the CoM back. Even if the disturbing movement itself is to fast to be controlled, see 4.1, the resulting disturbance can be leveled out with the help of the quasi-static controller resulting in a stable motion.

In figure 4(c) the movement resulting from the previous controlled kick is exactly repeated without the use of the feedback control. But this time an additional counterweight of 370 g is attached at the left side of the robot. The deviation of the CoM position leads again to the fall of the robot. In figure 4(d) it can be seen that the robot compensates this imbalance caused by the counterweight using the sensor feedback by shifting the whole motion to the right.

The benefit of the proposed integration of sensor feedback becomes clearly visible. Without explicit knowledge of the deviation the robot is able to adjust to unforeseen forces acting during the execution The used sensor information allows an adaptation of the defines key frame motion stabilizing the otherwise unstable motion.

5 Conclusion

This paper presents a way of combining the classical method of motion design by key frames with control algorithms for postural stability. Proof of the soundness is presented in the application to kicking motions for robot soccer. A great improvement to the robustness could be shown which even enabled the robot to perform its kick successfully with additional weights attached to it.

While uncontrolled replaying of predefined motions is still common for kicking in RoboCup leagues involving legged robots, this approach represents a far more robust and general alternative. Neither do motions need to be adapted for separate distinct robots nor do they need redesign in case of hardware wear of small decalibration of joint motors. The profit of this is obvious in the presented case and can also be of benefit in other applications involving environment interaction.

Further improvements can be achieved by introducing a model more complex than the simple quasi-static control of the robot's center of mass. Besides this, the next subject of interest is the integration of such motions directly into the robot's normal walking. This is a challenge both for motion generation and for perception accuracy that would enable faster, more fluid and natural motions and therefore faster robot soccer games.

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