LOW-DIMENSIONAL USER CONTROL OF AUTONOMOUSLY PLANNED WHOLE-BODY HUMANOID LOCOMOTION MOTION TOWARDS BRAIN-COMPUTER INTERFACE APPLICATIONS

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The goal of the presented work is to use a low-dimensional control interface to control the high-DOF whole-body locomotion motion of a humanoid robot, for instance using a 2D keyboard or joystick interface (up-down, left-right) to control a 30 DOF acyclic locomotion task (reaching a goal position by climbing on a stair). This work is motivated by the use of non-invasive BCI, which offers only such low-dimensional control signals, for low-level motion control of humanoids or exoskeletons in the assistive robotics domain of applications. The methodology is the following: given the target complex locomotion task, the humanoid autonomously plans the high-DOF motion and then executes it allowing the user to control on-line some low-dimensional features of the motion, namely way-points of the moving end-links. The approach is based on the two-stage contact-before-motion planning paradigm, which autonomously plans a sequence of transition contacts in its first stage, then executes the collision-free dynamics-consistent motion in the second stage, keeping dynamics balance of the motion. Example of this control approach is demonstrated in dynamic simulation.

Keywords: Whole-Body Motion Planning; Humanoid Locomotion; Motion Autonomy.

1. Motivation of the Work

Control of humanoid robots through brain-computer interface (BCI) is an active field of research that raises challenging planning and control problems and that can develop into promising assistive applications for the elderly or reduced-mobility people. The humanoid design allows the user to intuitively comprehend the kinematics and dynamics of the controlled device, and allows the device to be readily used in a human-targeted living environment as such, i.e. without adaptation of the living environment to the device.

Previous work on control of such humanoid systems do not however take full profit of the dexterity of the humanoid design. In Refs. 1 and 2, the humanoid is seen as a continuously walking machine that is “steered” with the BCI the same way a mobile manipulator would be, for example as it is actually the case in Ref. 3. The specificity of a legged device over a wheeled one thus do not emerge within the range of applications spanned in these works. In particular, dealing with slightly differently structured environment, such as one with stairs, would not be straightforward. We do acknowledge that since these works rely on state-of-the-art walking pattern generators, they will naturally benefit from the advances in such pattern generation methods that can, for example, autonomously deal with variable stair heights or non-flat terrain.[4–7] They can also benefit from the hierarchical architectures in which they are embedded[3,8] that would allow them to be wired to alternative behaviors when facing stairs for instance. We nevertheless investigate a different approach, based on our previous work of complex whole-body motion planning and control of humanoid robots. We believe that through a more generic motion approach, the device can prove more efficient in coping with the many unpredictable situations that often occur in real life and would not have been accounted for in the said hierarchical architectures.

As we are aiming for non-invasive brain-signal-acquisition methods such as using an EEG cap for example, one can only expect to have at his disposal low-dimensional low-resolution signals to be mapped to the high-DOF kinematics of the humanoid. State-of-the-art non-invasive BCI control achieved precise control of a two-dimensional cursor position on a screen by spinal cord injury patients.[9] In Ref. 10, subjects rapidly learned to accurately control the position and speed of a one-dimensional cursor on a screen using various motor imagery (imagining repeating the word “move”, or tongue/shoulder/hand imagery). One of the latest studies carried out at our institute shows that two-DOF finger movement can be reconstructed in real time from the brain activities extracted by Magnetoencephalogram (MEG).[11] From these studies, we can expect that the development of a method to extract two-DOF control command from the brain activities by using non-invasive and not-too-expensive measurement device in real time will become realistic. We take these results as a premise for the controlled feature selection in the high-DOF motion of the robot. We thus present in this work a control interface for two 1-dimensional (2x1D) features of the movement (step way-point target, step way-point threshold) than can be later interfaced with motor imagery BCI, proposing an alternative to the currently investigated visual-stimulation-based EEG such as SSVEP[2,3,8] or P300.[1]

2. Problem Formulation

We formulate our problem as follows: Given an initial and goal configuration for a humanoid robot, in arbitrary contact state with the environment, use a two-dimensional control interface to execute the motion of the humanoid from the initial to the goal configuration.

Let N be the number of degrees of freedom of the humanoid robot ($N \gg 2$, e.g. $N = 30$). The humanoid robot motion control requires an N-DOF command signal in the joint space, the problem can thus be reformulated as mapping the 2-DOF user interface command signal to the N-DOF whole-body motion of the humanoid robot, as schematically represented in Fig. 1.

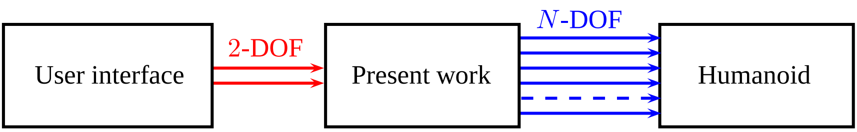

Fig. 1. Schematic representation of the problem formulation.

3. Methodology

The proposed approach is based on off-line autonomous planning of the N-DOF whole-body motion followed by on-line local modification of the planned motion, using the 2-DOF command to help the execution or correct the shortcomings of the autonomously planned motion, as schematically depicted in Fig. 2.

The motion autonomy framework consists of two components: an off-line contact transitions planner and an on-line controller that follows the prescribed contact transitions.

The initial and goal configurations of the humanoid robot do not necessarily share the same contact state with the environment (as it would be the case in Refs. 12–15), thus defining a locomotion problem, for which cyclic walking based on footsptep planning [16–18] does not necessarily provide a solution, since we allow the use of various links/bodies for support. We thus resort to our previous acyclic multi-contact planning framework.[19]

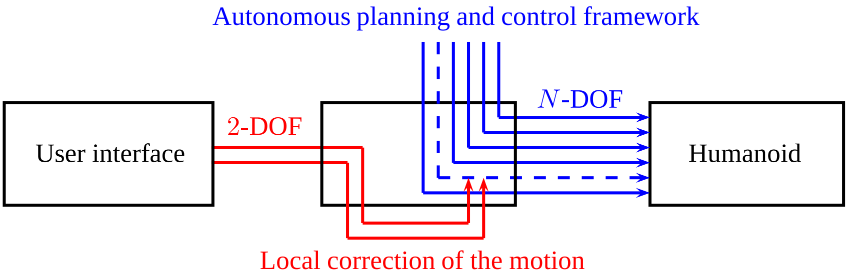

Fig. 2. Schematic representation of the methodology.

In this respect, the off-line planner only considers these initial and goal contact states, as inferred from the initial and goal configurations, and plans a feasible sequence of contact transitions between the two states, using a best-first search algorithm in the contact-state space.[20] Each contact transition is associated with a corresponding whole-body configuration generated by a physics-constrained inverse-kinematics solver.[21]

Given this planned sequence of contact states and associated configurations, the on-line controller[22] executes a whole body motion of the humanoid going through the sequence of steps by solving at control frequency a quadratic program (QP) in the generalized accelerations, contact forces, and actuation torques of the robot, minimizing a weighted sum of squared task acceleration errors, under whole-body dynamics equation of motion, actuation, joint and torque limit, and friction cone linear constraints. The tasks are defined on the center of mass of the robot, on the moving end-link that changes its contact state in the current step, and on the whole-body configuration, according to a finite-state machine (FSM) that goes through three major states while executing the steps: 1) moving the whole-body while staying in the same contact state, 2) lift-off of a contact, and 3) touch-down of contact. The transition between the lift-off and touch-down phase when moving a contact link is triggered when the link goes through a heuristics-defined way-point (Full details on the online-generation of the whole-body motion is found in Ref. 22).

In the present work we add as a main contribution to this on-line controller an autonomous collision avoidance linear constraint in the QP formulated as a velocity-damper based on the Faverjon and Tournassoud method.[23] It acts as a repulsive field that keeps the link of the robot away from the obstacle, without preventing it from reaching its goal contact location, that acts in turn as an attracting field. This formulation might however get the moving link trapped in undesired equilibrium situations (that can be pictured as local minima of the resultant field), in which the link stays immobile under the combined actions of the repulsive and attractive fields.

This is where the user can use the two-dimensional command at his disposal in order to untrap the link, by moving the location of the way-point through which the link was heuristically prescribed to go. We thus choose to use the two-dimensional command signal to control the motion of the moving end-link during the step through intuitive control of the way-point. Since we do not want the moving link to stop (halt) at the way-point, in order to have smooth motion, we define the way-point only as far-away target to reach, and the transition is triggered when the link crosses a threshold plan while aiming for the far-away target, see Fig 3. One variable of the 2-DOF signal will be used to control the height of the way-point, while the other variable is used to control the height of the threshold plan, see Fig. 4 and details in Appendix A.

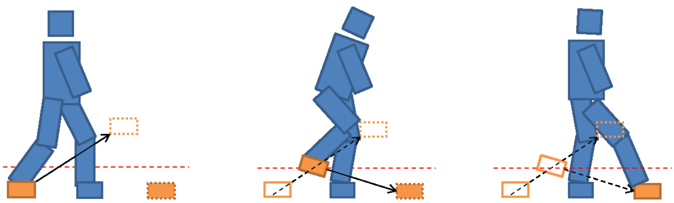

Fig. 3. The way-point and threshold strategy.

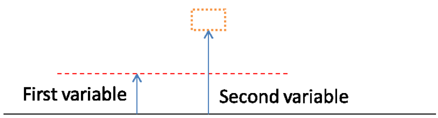

Fig. 4. The controlled variables with user interface.

4. Sample Results and Discussion

The video that can be downloaded at `www.cns.atr.jp/~karim/clawar2013.wmv` or `www.cns.atr.jp/~karim/clawar2013.mp4` demonstrates an example of use of the framework. In this example, the specified goal location of the robot is up on the stair. The framework autonomously plans the contact locations and intermediate static postures in the off-line stage to climb the stair (Fig. 5), then the on-line motion control scheme starts.

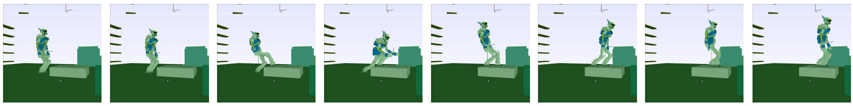

Fig. 5. The autonomously planned sequence of steps.

Whenever the FSM enters the contact lift-off state, the ambient color in the screen changes to a blue ambient color to indicate that the user can now control some features of the motion being executed. A black sphere and a blue wire frame plane are displayed to represent respectively the tracked way-point and the threshold plane (Fig. 6). When the contact body starts to move, it targets the position of the black sphere, until crossing the blue plane. At that point the FSM goes to the contact touch-down state, the ambient color of the screen is changed back to normal, and the user has no longer control on the motion.

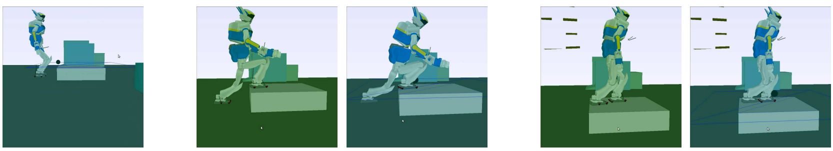

Fig. 6. Left: in user-control mode. The blue wire frame plan represents the threshold, the black sphere represents the way-point. Middle and right: two example transitions from autonomous mode to user-control mode.

In the video we demonstrate some extreme cases. By moving the blue plane high enough we are actually able to simply control the position of the contact body that tracks the black sphere. This allows to test the said extreme behaviors such as bringing the foot upwards until reaching hip and knee joint limits (Fig. 7, right), or positioning the black sphere inside an obstacle (Fig. 7, left). As required, in the first case the robot does not loose balance and the knee and hip joint do not violates the joint limits, and in the second case the collision avoidance constraints prevents the body from "penetrating in" (colliding with) the stair.

Four computer keyboard keys are used to move the black sphere up and down and the blue plane up and down. This control interface can be replaced

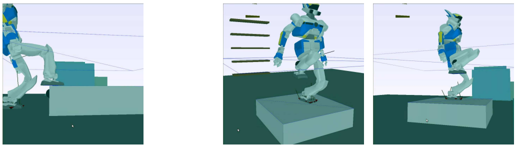

Fig. 7. Left: when the back sphere is positioned by the user inside an obstacle, the obstacle-collision-avaoidance constraint prevents the collision. Right: extreme motions imposed by the user, joint limits and equilibrium constraints keep the robot in safe configuration

by other devices, such as joystick, or, as discussed in the motivations of the work, a motor imagery BCI.

Finally, we plan in our future work to port this method from simulation to real robot. Among others, issues regarding the integration of real-time feedback of robot sensors should be dealt with in this perspective.

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Appendix A. Low-Dimensional User Control Variable Derivation

Figure A1 illustrates the following derivations. Let P_o denote the origin position of the contact body at the start of the current step, P_g be its aimed goal position at the end of the step (as planned off-line), $\mathbf{N}$ the normal to the contact surface at the goal position. The way-point W is defined as

$$W = P_o + \alpha\,(P_g - P_o) + h_1\,\mathbf{N}\,, \tag{A.1}$$

where α is a fixed coefficient between 0 and 1, typically $\alpha = 0.5$, and h_1 is the height of the way-point ($h_1 \in \mathbb{R}$).

The threshold is defined as a plan $(T, \mathbf{N})$ of origin point T and normal $\mathbf{N}$, T being defined as

$$T = P_g + h_2\,\mathbf{N}\,, \tag{A.2}$$

where h_2 is the height of the threshold ($h_2 \in \mathbb{R}$).

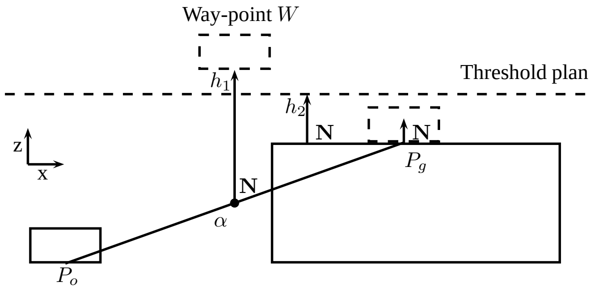

Fig. A1. User-controlled variables

The low-dimensional on-line controlled variables that we retained in this study are thus $(h_1, h_2) \in \mathbb{R}^2$.

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