A Human-Like Control for Sensorimotor Multi-Tasking in Humanoid Robots

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***Abstract*— This paper introduces a human-derived humanoid control concept that allows voluntary movements with automatic posture control. The concept consists of a modular control architecture, where each DOF is served by one control module. The control modules are based on the DEC model (DEC, Disturbance Estimation and Compensation). The DEC model combines sensory-derived disturbance estimates for re-active disturbance compensation with predicted-sensory disturbance estimates for compensation of self-produced disturbances. The control modules are interconnected, forming a network whose functionality dynamically reflects the robot's current state of kinematic activity and its interaction with the external forces that are acting on it. By this, the DEC control allows superposition of several postural and voluntary activities.**

Keywords—Humanoid; Multi-Task Control; DEC model

I. INTRODUCTION

In order to move the body during walking or to manipulate objects, humanoid robots need to combine their voluntary sensorimotor actions with posture control, which includes maintaining body balance, adopting adequate body-link poses, inter-link movement co-ordinations, and more - which reflects what humans are doing. In posture control, balance control is a fundamental function strictly constrained by physics. And, balancing in the real environment requires the robot to adapt its sensorimotor control to changing environmental conditions. The model presented here, the DEC (disturbances estimation and compensation) model, meets the demands of combining voluntary movements with posture control and with adapting posture control to external conditions.

The DEC model was originally synthetized on the basis of human psychophysical experiments and was validated in human posture control experiments (Lit). A control model was derived from the human data and implemented into robotic platforms. Robotic experiments were performed in the human testbed for comparison with the human data. The robotic tests have been performed with several robotic platforms[9][12][13][14]. The tests reproduced in a stable way the human responses to external stimuli (e.g. support surface tilt) in terms of amplitude and frequency response functions [7]. In the DEC framework, sensory reconstruction in a multisensory control module is used for estimation of external disturbances and their compensation. Multisensory integration includes vestibular, visual, and joint angle and joint torque proprioceptive inputs. Four estimators account for the four relevant external disturbances (field forces such as gravity, contact forces, support surface rotation and translation). Thus, compensation is disturbance specific. In addition, the overall weight of a given sensory input is automatically adjusted in relation to disturbance modality through interactions between estimators. Further, the effect of each estimator is adjusted to disturbance magnitude by detection thresholds, by which humans respond proportionally stronger to large than to small disturbances. These phenomena are referred to as *sensory reweighting*. A change in visual cues availability (e.g. eyes open or closed) is explained by sensory fusions (e.g. visual-vestibular; Lorenz 15).

The DEC model so far allows reproducing human balance responses in the ankle and hip joints to unforeseen

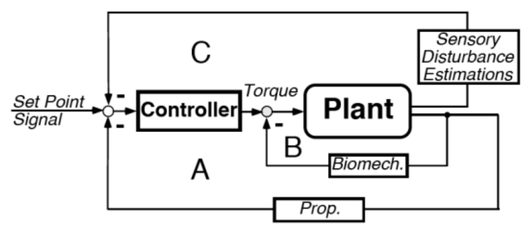

Figure 1 Simplified scheme of DEC model

external disturbances in special purpose and humanoid robots. Comparing human behavioral observations with model and robot simulations provided inspirations on how humans combine voluntary movements with the re-active DEC in a modular control architecture. This is described in abbreviated form in the following, explaining basics of the DEC control(II), generalization of the disturbance estimations in multi-DoF systems (III), fusing with voluntary movements predicted-sensory estimates of self-produced disturbances and sensory-derived disturbance estimates (IV), assigning tasks to the modules (V), and ending with Discussion and future work. The displayed concepts may be appealing and inspiring for the control of humanoids as long as humans are still superior to robots with regard to sensorimotor versatility and failsafe robustness.

II. THE DEC CONTROL

Figure 1 shows in simplified form the DEC module as it was developed for the human control of ankle joint torque in conditions that allowed simplification of biomechanics in terms of a single inverted pendulums (SIP; [14]). The module controls joint position of a moving link with respect to a supporting link (e.g. the feet) and consists of three parts: (A) Proprioceptive negative feedback loop of joint angular position (box 'Prop.'), (B) Intrinsic stiffness and damping loop of musculoskeletal system ('passive stiffness' in box 'Biomech'), and (C) the DEC loops. The DEC loops, four in a complete scheme, estimate the external disturbances through sensor fusions and command via negative feedback the servo (represented by A and B together) to produce the joint torques that compensate for the disturbances. If disturbance estimation and compensation were ideal, the servo would function as if there were no disturbances, producing according to the set point signal a desired pose or movement [1]. However, human typically under-estimate and under-compensate unforeseen external disturbances, which has been attributed mainly to sensor noise and inaccuracy[15][16][17]. A proportional-derivative factors (PD) controller is assumed. Its static gain is limited in humans by neural time delays (estimated as lumped delay in the order of 160 ms).

As detailed elsewhere[14], the vestibular HS signal arising in the head is used directly of HS control, but in addition also for controlling other body links by corresponding transformations. For example, the HS signal is 'down-channeled' for controlling trunk in space angle, TS, using neck (head-to-trunk, HT) proprioceptive information (TS= HS - TS) and further via the leg segment to estimate the rotation of the foot support in space (FS; estimate used for support surface tilt compensation, giving firm haptic contact, through one of the DEC loops). Using an analogue down-channelling of the vestibular HS signal to the COM representation of the body (above the feet) allows to estimate the body's gravitational ankle torque. Estimation of support surface translation in the DEC concept uses in addition to proprioceptive signals vestibular head-space linear acceleration and angular velocity signals, while estimation of external contact forces ('external torque estimate') involves joint torque sensors. This concept can be extended to multi-DOF as shown in [9] for two degrees of freedom and in [8] for the general case, in the following the general case will be described.

The effects of the external world on the body are expressed in terms of external disturbances. Humans use multisensory integration of for their postural control [2]. Studies on human self-motion perception [3] and animal work on sensory processing [4] showed that the central nervous system internally processes physical variables that are not directly available from the sensory organs, but result from sensor fusions.

Four physical *external disturbances* need to be taken into account for posture control: support surface rotation (platform tilt), gravity and other field forces, support surface translation (external acceleration) contact forces (external torque).

III. GENERALIZATION OF DISTURBANCE ESTIMATIONS

1) Support surface tilt

For the n^{th} link in a multi-DOF system (Fig. 2), the link orientation in space is given by α_n^{SPACE}. This information is obtained from vestibular input that is down-channeled through the fusion of vestibular and proprioceptive signals by

$$\alpha_n^{SPACE}=\alpha_{n+1}^{SPACE}-\alpha_{n-1}^{JOINT} \quad . \tag{1}$$

The down-channeling proceeds from the upper most segment α_{HEAD}^{SPACE} that contains the vestibular organs. The tilt of the lowest link in the system (most often the foot), which provides the support for the upper links, is given by

$$\alpha_0^{SPACE}= \alpha_{HEAD}^{SPACE}-\sum_{k=1}^{N}\alpha_k^{JOINT} \quad . \tag{2}$$

Human experiments [10] suggested that the down-channeling to the supporting link occurs through velocity signals. Thresholding (dead band discontinuity), gain scaling and integration are performed on α_0^{SPACE}, from where the tilt estimate is then up channeled for controlling the tilt responses of the upper links.

2) Gravity

The gravity torque, τ_g is calculated as

$$\tau_g=m_n^{UP}\, g\, CoM_{nx} \tag{2}$$

where m_n^{UP} is the mass of the body above the controlled joint, CoM_{nx} is the horizontal component of the position of the center of mass $\boldsymbol{CoM_n}$ of all the segments above the controlled joint. The gravity compensation in each joint comprises all links above this joint

3) Support surface translation

The part of the vestibular head acceleration signal that is not explained by trunk rotation at any joint below is taken to stem from support surface acceleration. This is expressed as $\boldsymbol{a}^{EXTERNAL}=\boldsymbol{a}^{VESTIBULAR}-\boldsymbol{a}_n^{SELF}$, where $\boldsymbol{a}_n^{SELF}$ is the acceleration produced by joint movements. The disturbance torque then is

$$\tau_{acc}=a_x^{EXTERNAL}CoM_{ny}m_n^{UP}+ a_y^{EXTERNAL}CoM_{nx}m_n^{UP} \tag{3}$$

4) External torque

The external torque can be expressed as:

$$\tau_{ext}= \tau_n^{a}- \tau_n^{g} - \tau_n^{in}-\tau_n^{p} +\tau_n^{A} \quad . \tag{4}$$

the total torque τ_n^A acting on the joint is

$$\tau_n^{A}= \frac{d}{dt}(\dot{\alpha}_n^{SPACE} J_n^{UP}) \tag{5}$$

where J_n^{UP} represents the moment of inertia of all the segments over the controlled joint, Also the quantity J_n^{UP} *is* downchanneled nad updated locally for each module.

5) Frontal plane control

In order to apply the DEC control in the frontal plane a formalization of the body kinematics as a double inverted pendulum has been implemented. The lower limbs can be represented as virtual ankle joint (between the two actual feet) connected by a virtual link to the pelvis joint, that is the one connecting the trunk and the hip. This modeling has been proposed also for the interpretation of human balancing in the frontal plane in [12]. The desired torque for the virtual joint is distributed on the four actuated joints (ankles and hips)[11]. For a more detailed description of the DEC concept, with examples from the SIP case see [8].

IV. VOLUNTARY MOVEMENTS

Most disturbances that are arising with pro-active (voluntary) sensorimotor behavior are self-produced and thus predictable as to their sensory and postural consequences, for example the gravity effect during a voluntary body lean forward. Predicted-sensory disturbance estimates are thought to have clearly shorter time delays, higher accuracies and less noise than the sensor-derived estimates. It is reasonable to assume that humans learn these predictions, typically experiencing the effect of the voluntary movement multiple times per day. Figure 2 shows the integration of the predictions with the sensory estimate in DEC. The prediction involves two steps. First, a version of the prediction is run through an internal model of the sensory disturbance estimate and subtracted from the actual one, so that in the absence of external disturbances only the second, direct version of the prediction become effective. In case that also some disturbance of external origin overlaps, its effect combines with that of the predicted disturbance. This allows coping with superposition of externally arising and self-produced disturbances.

Preliminary robot experiments showed the possibility to integrate this principle with an online learning system of self-produced disturbances. And, simulations showed that DEC may be extended with a compensation of self produced coupling forces [18].

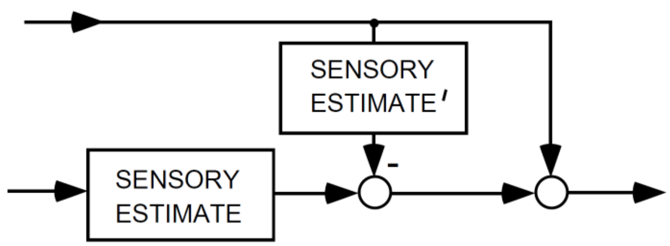

Figure 2 Principle of fusing sensory estimates of external disturbance with predicted-sensory disturbance estimates.

V. CONTROLLED VARIABLES AND EMERGENCY OF SYNERGIES

During many motor behaviors such as standing and walking, humans tend to maintain an earth-vertical body posture, where the axial links represent a stack of superimposed body segments. In this stack, the various DEC modules and their DOFs may serve different functions, which in the DEC concept are realized by using different controlled variables defined by the set point signal of the servo controller. Examples are shown in Fig. 3, where the set point signal of a given joint is set according to the task (lower case letters represent internal representation; signals ts, fs, and lf encode trunk-space, foot-space, and leg-foot angles; G, gain factor; Cont., controller; open box, calculation of body-COM-space angle). For balancing body equilibrium in the ankle joints, the input switch is set to BS! (meaning that the desired input is a vertical orientation of the body COM above the joint). The switch setting entails that the servo feedback is a body COM-in-space angle signal, which requires evaluation of the momentary body COM location. In other behavioral scenarios, the task for the ankle joint may be a given orientation of the leg segment in space (switch setting LS!) or a given leg-foot pose (LF!). In a chain of several modules, combing movement and pose tasks via the set point signals allows for a multitude of action patterns. This may serve to simplify the control of sensorimotor behavior.

Since the high dimensionality of the human motor system has been addressed by Bernstein [6], many suggestions for its simplification were made, such as various forms of motor primitives and muscle or movement synergies. Notably, human-like movement synergies emerged in simulations of the DEC model [7]. Figure 4 shows as example a voluntary trunk forward lean of a simulated agent. The leg links, Thigh and Shank, together are leaning backwards, so that the Body COM remains above the ankle joint. In this example, the ankle joints are balancing the body COM as a whole (controlling BS!), while the knee joints control locally to keep the legs straight, and the hip joints are commanded to bend forward. The ankle-hip coordination automatically arises from the interaction between the hip and ankle control modules and the agent’s biomechanics. It is conceived that this kind of movement coordination may also be learned and initiated pro-actively, for example in highly trained sports activities.

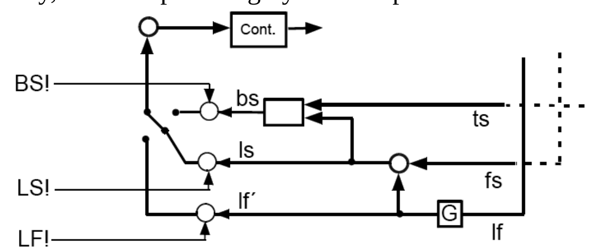

Figure 3 Different set-point signals for a DEC module

VI. DISCUSSION AND FUTURE WORK

The presented modular system represents a concept on how humanoids may use sensors to control the many degrees of freedom involved in the control of posture and movements. The inspiration for the concept is derived from a human sensorimotor control scheme that has been synthesized on the basis of psychophysical experiments and has been identified from human balancing responses to external disturbances. The control system requires desired set point signals for the different controlled variables and, when needed, it can accept a desired voluntary movement as reference. The emerging global behavior results then from the interaction between the different modules.

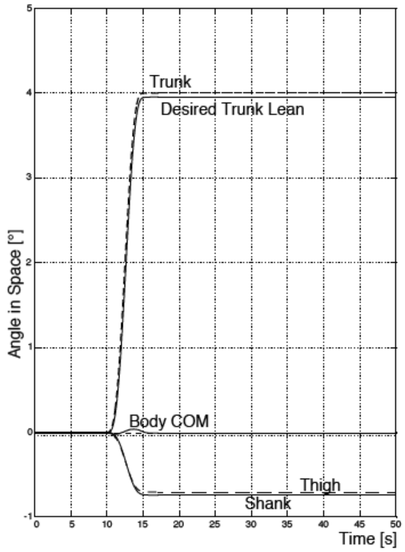

Figure 4. Voluntary forward trunk lean in the hip joint.

Future aims with the DEC concept are a robot implementation of gait (as provisionally tested in simulation). Particularly challenging that the control modules in DEC are organized as a *stack* of modules, in which the module of one DOF is connected with the modules controlling the adjacent joints. The order of the controllers in this chain of connections is determined by the position of the controlled joint in the body. When one leg is lifted in order to take a step, the links of this leg stop to contribute to the support of the body and start to belong to the part of the body that is supported by the other leg. This means that generally for such kind of change in body or body-support configurations, an additional set of control modules is needed and a higher-level control system that commands the switching between the two modules. So far, the target variables, as well as their desired values, were set manually for fitting the model to the requirement of a given experimental situation and its demands. The higher-level model that sets the variables required for a generic task remains to be defined.

Ongoing developments of the system also aim to control gait in a human-like and generalized way that allows adjusting it to changes in external and bodily conditions. Furthermore, a aim is to trigger complex tasks such as walking or reaching by a voluntary movement using a small subset of controllable variables, while the remainder of the coordinated movement should emerge from the interplay between control modules. It is envisaged, for example, that a hand reaching follows a reference movement for the hand effector, while necessary adjustments of body posture and assisting movements (e.g. by trunk bending or a step) emerge automatically from the task.

VII.

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