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Human Equilibrium Control Principles Implemented into a Biped Humanoid Robot

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Abstract. We describe how human equilibrium control principles, which were derived from neurophysiological experiments, can be implemented in a biped humanoid robot (‘PostuRob’). Stance control in humans uses sensorbased feedback which involves mainly three sensors that measure: (1) body motion in space (vestibular system), (2) body motion with respect to the feet (ankle angle proprioception), and (3) torque between body and feet (ankle torque proprioception). The sensor signals are not used directly for feedback, but instead are used to internally reconstruct the physical stimuli in the outside world by means of sensor fusions. These reconstructions yield internal estimates of the external force fields such as gravity, the external contact forces (e.g. push), and support surface motion. The estimates are fed into an ankle angle proprioceptive feedback loop. By way of the signal fusions the robot‘s control adjusts to the external stimulus situations, a fact that allows for low loop gain and robust control. This control differs from that of the biped robots described in the literature. They tend to use a global stability measure such as the COP (centre of pressure) or ZMP (zero moment point) and this control does not adjust to the external stimulus situation. Our PostuRob is used in a biorobotics approach to better understand stance control deficits of neurological patients and the effects of therapy and rehabilitation.

1 Introduction

Can we nowadays claim that we understand the control principles of human upright stance well enough to use them as blueprints for constructing an equilibrium control system of a biped robot? Given this, can we use such a robot in medical research for better understanding impaired stance control in patients and the effects of therapy and rehabilitation? Finally, in which way does the presumed human control principles differ from the engineering ones currently used in robotics? We refer to these three issues, which emerged from our current research, as ‘demonstrator aspect’, ‘biorobotics aspect’, and ‘bionics aspect’.

Demonstrator aspect. Biological research nowadays uses more and more dynamic computer models to formalize and simulate identified sensorimotor functions and this even when they contain non-linearities (example in Maurer et al. 2005). This also applies to the research of human control of upright stance (van der Kooij et al. 2001; Peterka 2002; Mergner et al. 2003). These models may well serve as blueprints for constructing corresponding machines. But why should we implement them into machines instead of relying on the computer simulations? One reason is that successful implementation of the models into real world media adds credit to their validity (the demonstrator aspect). For our colleagues, the functioning of our robot (Fig. 1) has indeed a much higher explanatory and persuasive power than our computer models had in the past.

Biorobotics aspect. Another reason to implement the biological models into robots is that they may be used in biological research (biorobotics). There has recently been a extended debate on this approach (Webb 2001; target article plus comments). The following aspect, however, has not been sufficiently addressed. Imagine the investigation of a neurological patient on a motion platform in a posturographic laboratory with the help of various devices for measuring kinematic and kinetic parameters. The complexity of this situation poses problems when we try to mimic it in computer simulations for comparison of simulated and experimental data, because the many simplifications and formalizations required for the modelling move us away from reality. The problem may partially be resolved by applying a new method, the so-called *'hardware in the loop (HIL)' simulation.* In this approach only the control mechanism under consideration is implemented as a software model on an 'Embedded PC' (real-time; under control of a host PC), while all other components remain hardware. In our example, this would mean that we can use the laboratory and its recording equipment as before, replace the human body with its sensors and actuators by a humanoid robot, whose "brain" (Embedded PC) contains a software model for human stance control (Fig. 2). We therefore hold that our medical research can well take advantage from biorobotics.

Figure 1: Photograph of 'PostuRob' on motion platform. Its aluminium skeleton consists of two rigid legs fixed to a pelvic girdle and a spine ('body'). Centre of mass is mainly represented by two plumb weights on pelvis. Each leg carries a front and back pneumatic 'muscle' with 'tendons' (springs) to move the body with respect to the foot about the 'ankle joint'.

Bionics aspect. As to the differences in the control principles between humans and previous robots, one may predict that robot technology may profit from the use of biological principles (bionics). This notion intuitively draws on several basic differences, such as that the control strategy of humans have developed during million years of phylogenesis, while the engineering sciences are rather recent, that the rather compliant human tissues is advantageous over the metallic materials the robots are currently built from, and so forth. But we will try to answer the question more specifically.

A difficulty in this comparison may arise from the fact that there exist considerable differences among the equilibrium control principles currently used in biped robots. However, it appears common to most of them to use sensorbased feedback, calculating from the sensor inputs a global stability measure such as the COP (centre of pressure) and ZMP (zero moment point) etc. and to use this to keep the robots equilibrium within stability limits (example, Popovic et al. 2005). This principle leaves open which of the external stimuli is causing a given perturbation. In contrast, the human control principle reconstructs from different sensors the external stimuli and uses these estimates for feedback control, as we will show.

In the following, we first describe the most relevant sensors used by humans for their control of dynamic behaviour in space and give technical equivalents. Then, we describe the principles that humans use to fuse the sensor signals for their self-motion perception and posture control. Furthermore, we explain how we implemented these principles into the robot and mention first results. Finally, we report on its possible applications in medicine and point out difference as compared to the classical engineering way to implement such a control task.

2 Sensors and sensor fusion principles

From physiological and clinical work, it is known that the following sensor systems play an outstanding role in the control of human dynamic behaviour in space:

(1) **Gravito-inertial "body-in-space" sensor - Vestibular system**. Anatomically, this system is located in the inner ear of the skull and consists of two parts, the macular (or otolith) organs and the semicircular canals. Their functions are those of a 3D accelerometer and a 3D gyrometer, respectively. The fact that humans are able to distinguish between head tilt and linear acceleration despite the equivalence principle has been explained by a '*canal-otolith interaction'* in the central nervous system, CNS (Mergner and Glasauer 1999). This interaction represents a sensor fusion that yields three sets of signals of body motion: (a) 3D rotational velocity, (b) 2D angle with respect to gravitational vector, and (c) 3D linear acceleration. The vestibular signals, unlike the other sensor signals, appear to show pronounced slow spontaneous fluctuations (Mergner et al. 2001) reminiscent of 1/f noise.

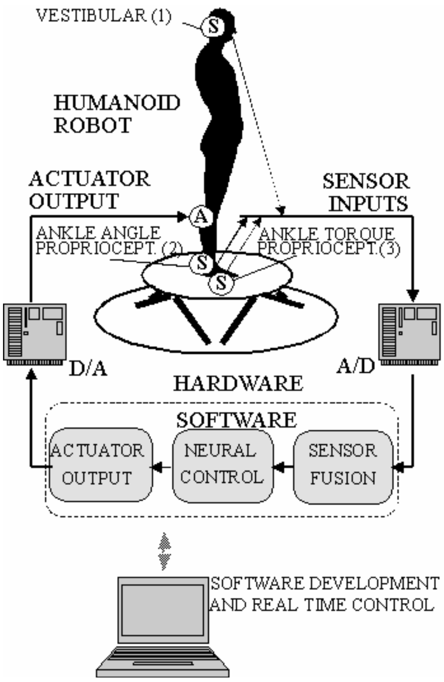

Figure 2: HIL simulation with actuator (A) and sensors (S)

(2) **Joint angle sensor (kinematic proprioception).** The position sense of the limbs is known to involve muscle spindle receptors as well as receptors in the skin and in the capsules of the joints. Humans combine these inputs in the CNS to a joint angle signal and, for special purposes, a joint angular velocity signal. A simple technical equivalent would be a goniometer.

(3) **Joint torque sensor (kinetic proprioception).** This measure appears to involve Golgi tendon organs in the muscle tendons (Duysens et al. 2000). During upright stance, humans also use somatosensory foot sole pressure receptors deep in the foot arch to ob-

tain a measure of the Centre Of Pressure (COP) (Maurer et al. 2000) which upon force closure between foot and support can be used as an equivalent of ankle joint torque (van der Kooij et al. 2005). In the robot, one can derive a measure of joint torque from force sensors under forefeet and heels of the robot's feet and/or from force sensors in the muscle mountings.

There are certainly many more sensor systems involved in human equilibrium control, for instance visual sensors. The three suffice, however, to explain the control principles. Their dynamic properties need not be considered here, unless stated otherwise.

Sensor fusions. They are considered in biology often under the view of redundancy effects where a given performance profits, e.g. in terms of temporal and spatial accuracy, from involving two or more sensors rather than one. Therefore it is important to note that each of the above three sensors provide distinct aspects of the physical stimuli, with redundancy occurring only in certain stimulus conditions (e.g., only if the foot is stationary in space is a given body-in-space angle equal to the body-to-foot angle). Using different sensors, appropriate sensor fusions may resolve the problem of *underdetermination of a physical stimulus by the signals of a single sensor*. We learned these lessons in psychophysical experiments of human self-motion perception (overview, Mergner 2002). A general rule drawn from these experiments was that humans in their perception tend to reconstruct from several sensory sources the underlying physical stimulus.

Our psychophysical studies suggested that these sensor fusions play a role also in sensorimotor control (Mergner et al. 1997). When we presented our subjects with vestibular as well as neck and leg proprioceptive stimuli during head, trunk, and leg rotations, we observed that they use proprioception in two ways: (1) for their perception of intersegmental motion, and (2) to perform with its help coordinate transformations of the vestibularly derived space reference from its origin (vestibular organ) in the head via the trunk to the feet and their support. Applied to postural control of upright stance, this could mean that (i) ankle angle proprioception is used in a feedback loop for body-on-foot(support) stabilization, and (ii) a vestibularly derived signal of support-in-space motion is fed into this loop and upgrades it into a body-in-space control.

Human perception during dynamic behaviour in space deals with the kinematic aspects of this behaviour, while the kinetic aspects (dynamics) tend to remain subconscious (Mergner 2002). Yet, with the general sensor fusion rule (internal reconstruction of external stimuli) we were able to include the kinetic aspects into a concept on how humans control their upright stance and we performed preliminary tests (Mergner et al. 2003). Care was taken to include all relevant external stimuli (i.e. body support surface motion, force fields such a gravity, and contact forces) as they would occur, for instance, during the following scenario: "The waiter on the ship brought me a glass of beer. Without looking at it, he balanced it across the swaying deck through a pushing crowd."

Human posture control studies. Our concept was finally tested in experiments. To this end, we simplified the 'waiter on the ship' scenario in that we restricted all stimuli to the sagittal (anterior-posterior) rotational plane and ascertained that, with small external stimuli, all rotations occurred primarily in the ankle joint. Subjects stood on a motion platform that was used for the support motion stimulus and, furthermore, pull stimuli were applied to their bodies by means of cable winches. These simplifications allowed us to model the scenario as an 'inverted pendulum'. It will be described together with the other parts of the model in the next section. Comparing simulated with experimental Bode plot data in a parameter identification procedure, model parameters were determined and, furthermore, changes in sensor weights across stimulus conditions were quantified. The results are published elsewhere (Maurer et al. 2005). They clearly show that human equilibrium control can be described by a sensorbased feedback model. This enabled us to take our model as a blueprint for constructing the robot.

3 The blueprint

The *'inverted pendulum' model* (Fig. 3) consists of two parts, a body (head, trunk, and legs) and the foot and its support. Both parts are inter-connected by the ankle joint. Primary body position is upright and foot position level, with the body weight pressing the foot firmly on its support (i.e. a motion platform; Fig. 1). Ankle torque T_{ank} in Fig. 3 results from muscles (actuators, assumed to be ideal, not shown) that produce torque and from passive torque (due to viscous-elastic muscle and elastic tendon properties; box BIOM, for biomechanics). It determines the COP. The torque affects body-in-space position *BS* depending on body inertia (box 'BODY INERTIA'). *BS* excursion in turn tends to lead to a COM (centre of mass) gravitational torque (T_{grav}; via box GRAV, for gravity), as does an external pull stimulus on the body ('External Torque', T_{ext}). Body-to-foot angle *BF* depends on *BS* and foot-in-space angle *FS* in the form of $BF = BS - FS$ (*FS* stems from tilt of the support surface and thus serves as tilt stimulus input). Details of these and the following parts of the model are given elsewhere (Maurer et al. 2005).

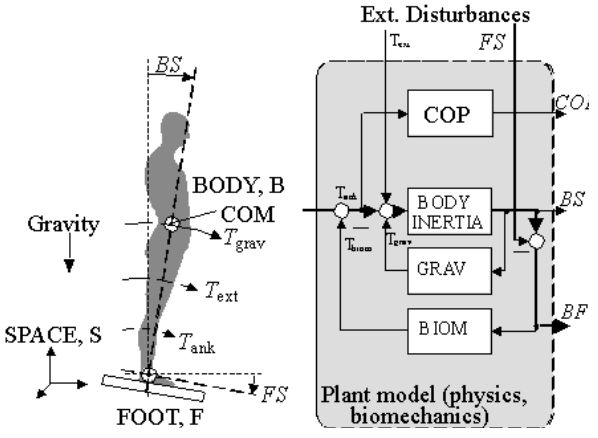

Figure 3: Plant model (arrows indicate direction sign of torques)

The mechanical part is combined in Fig. 4 with the sensor part (S), sensor fusion part (F), and controller part (C) of the model. The output signals of the mechanical part (COP, BS, BF) are used as inputs of the *three sensors* described above (ankle TORQUE SENSOR, body-In-SPACE SENSOR, and ankle ANGLE SENSOR, respectively). Their outputs provide measures of T_{ank} (τ_{ank}), BS (*bs* and first derivative $b^{\cdot}s$), and BF (*bf*, $b^{\cdot}f$) .

Sensor fusions. The external mechanical stimuli are given by the support surface motion (FS), the contact force (T_{ext}), and gravity (T_{grav}). Their reconstruction is shown in part F of the model (Fig. 4) in terms of the following internal estimates:

Estimate of support surface tilt FS, *fs*. The internal estimate *fs* is derived in the form of $f^{\cdot}s = b^{\cdot}s - b^{\cdot}f$ (a coordinate transformation of the space reference to the support surface), with $f^{\cdot}s$ then being fed through a detection threshold and a velocity-to-position integration. Subsequently, the *fs* signal is fed into an ankle angle proprioceptive feedback loop, which serves body-on-foot stabilization ('local loop') and is upgraded into a body-in-space stabilization by $fs + bf = bs'''$. Note that bs''' is determined by the ANGLE SENSOR signal bf when FS= 0° (stationary platform, fs= 0°), while it becomes mainly determined by the In-SPACE SENSOR during platform motion (bf and $b\dot{}f$ contributions to bs''' then tend to cancel each other). Note furthermore that not only motion or inclination of the support surface may lead to a fs feedback contribution, but also compliance and unevenness of the support surface.

Estimate of the COM's gravitational torque T_{grav}, τ_{grav}. The estimate of τ_{grav} is proportional to, and hence derived from the vestibular body-in-space signal bs (box aG2 contains transforming and gain factor). Since here the head is fixed on the trunk, no coordinate transformation of the in-space signal from the head to the COM in the trunk is required. τ_{grav} is passed through a threshold and then back transformed (box b) into an equivalent of a body-in-space signal, bs'.

Estimate of the external torque T_{ext}, τ_{ext}. The estimate τ_{ext} is obtained by combining τ_{ank} (output of TORQUE SENSOR) with bs-derived predictions of the COM's gravitational torque and the actively produced torque (in box 'Torque*'; see Maurer et al. 2005 for details and low-pass filtering of the constituents, not shown). After passing it through a threshold, τ_{ext} is transformed into a bs equivalent, bs''. Note that bs'' adds to the feedback only to the extent that an external contact force is applied. This may not only be a push or pull stimulus, but also an extra load on the body or a change in load distribution. Note furthermore that the gravitational term in box 'Torque*' is negative so that the contribution of bs via τ_{ext} tends to cancel that via τ_{grav}. Thus, bs from the In-SPACE SENSOR contributes to the feedback only if the TORQUE SENSOR is dismissed (together with box 'Torque*') .

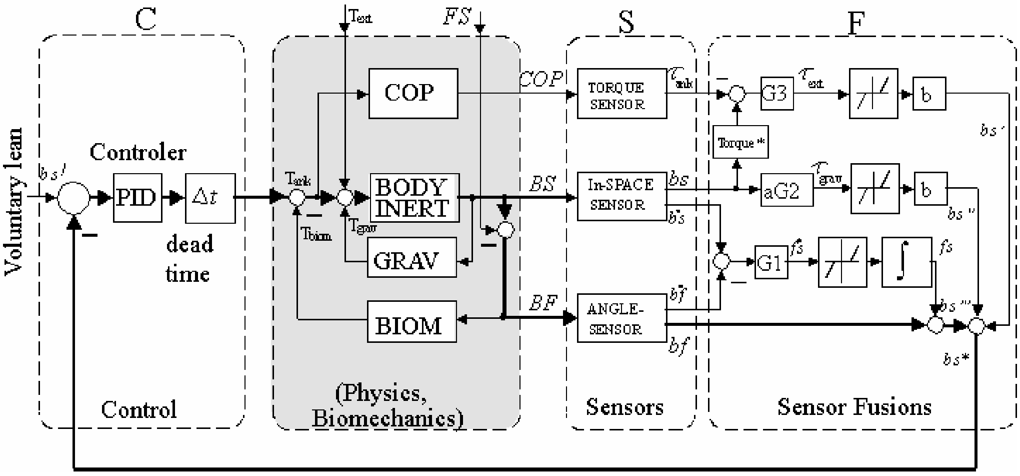

Figure 4: Blue print in the form of a block diagram ('local loop' in bold)

The bs', bs'', and bs''' signals are combined to one feedback signal $bs*$, which is subtracted in the Control part of the system from the voluntary command signal bs^{l} (Fig. 4). The controller (box PID, for P, proportional, I, integrative, D, differential factors) is adjusted to produce an adequate corrective torque. The various delay times in the system are represented by a single dead time element (box Δt; taken from human data to be 150 ms). As mentioned before, the control is implemented in Simulink/Matlab on an Embedded PC under control of a host PC (Fig. 2).

We refrain here from explaining the role of velocity and position thresholds in the sensor fusions; they were observed in our human posture studies, represent central mechanisms rather than sensor properties, and are involved in sensory re-weighting mechanisms (Maurer et al. 2005).

A description of the robot's hardware (height, 1.9 m; weight, 100 kg) with actuators (pneumatic muscles) and sensors as well as the relevant model parameters are given elsewhere (online:

www.neurologie.uniklinik-freiburg.de/forschung/sensorfusion/PostuRob/).

At this web site, we also give first demonstrations of the robot's performance which show that its balancing behaviour resembles that of our human subjects.

4 Discussion

We take up the framework of Introduction, but slightly change its order.

Demonstrator aspect and bionics aspect. We show that equilibrium control principles of human upright stance, which we derived from biological studies, can successfully be implemented in the equilibrium control of a biped humanoid robot. Not surprisingly, the robot shows postural responses to external stimuli that resemble those of humans (similar gain and phase curves in Bode diagrams). Furthermore, the robot successfully performs 'voluntary' body lean movements while simultaneously compensating for support tilt and contact force stimuli, a task whose performance challenges even human subjects. Which features make the human control principles different from those currently used in biped robots? As mentioned before, the latter use for feedback control a measure of the robot's stability, which they extract from the sensor signals. In the human control, in contrast, fusions of signals from different sensors are used to reconstruct the physical stimuli that are causing the sensor signals. Thus, it regains information that is lost by the *underdetermination of physical stimuli when characterising them by single sensor signals*. The achieved estimates of the physical stimuli are then used by means of the feedback to create the appropriate countermeasures to these stimuli. By way or the estimates and their fusion in the feedback the control system adjusts to the stimuli and their composition (see above, estimate of T_{ext}) so that the overall loop gain can be low, a fact which yields a 'soft' and robust control that tolerates a relatively long dead time of the loop and sensor inaccuracies. Furthermore, active participation of the In-SPACE SENSOR in the control is largely limited to situations with support tilt (see above, estimate fs). In fact, it is this sensor which is the most inaccurate one among the three sensors used. The internal stimulus representation create a meta-level that in future applications may be suited for incorporating communicated, predicted, and stored knowledge about the stimuli into the estimates. Finally, upon failure of sensors and or sensor fusion components, the system's function is only partially impaired.

We hold that the robot's equilibrium control can be extended to the other planes of space including the translational ones. Note that we have not yet implemented an internal estimate of linear support acceleration explicitly, but implicitly the system in its present form is already coping successfully with this stimulus. The reason is that the stimulus leads by means of body inertia to a torque that becomes represented in the signal of the TORQUE SENSOR and the τ_{ext} estimate. We hold furthermore that the control is modular and therefore will allow us to add more body segments and joints and that it can incorporate further sensors as well as cognition.

Biorobotics aspect. As mentioned in Introduction, research of complex biological systems is performed more and more in a hypothesis-driven way with a back and forth between experiments and model simulations. We conceive that the HIL methods with a robot as hardware can help to overcome the problem arising from the fact that the formalisations and simplifications in modelling tend to make the model unrealistic. We expect that this approach will allow us to explore into human sensorimotor control functions and to develop concepts as to the malfunctions underlying sensorimotor deficits in patients and to therapies. An additional aspect is that the approach may help to construct neural prostheses and orthoses (exoskeletons in the form of shells around body segments, equipped with motors that guide, perform, or assist segment movements). They may be designed to aid patients with motor problems (e.g. paraplegic patients) or with sensory deficits (e.g. loss of sensors). *The technical realization of such orthoses would be rather straight forward, because parts of the robot and the HIL system can be directly transformed into the design.* We hold that this ‘human‘ control design has a much better chance to gain patients’ compliance than a pure technical one.

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