NEUROLOGICAL AND ENGINEERING APPROACHES TO HUMAN POSTURAL CONTROL

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Abstract: This paper discusses the human postural control as a system engineering approach problem. Two main approaches are considered: neurological and engineering. From the neurological perspective, the problem is described, main sensory systems are identified, sensor fusion is suggested, and control system architecture and details are presented. Experimental results on both human subjects and on a special-purpose humanoid agree with the presented architecture. On the other hand, the humanoid parameters are identified, the humanoid dynamic model is derived, external-disturbance estimation methods are presented, a control method for stabilizing the body motion and then for robust tracking of voluntary motion in the presence of external disturbances is shown. This constitutes an engineering approach to this problem. Simulation results are given and it is shown that the presented method is capable of estimating the disturbances and for controlling the motion.

1 INTRODUCTION

Human upright stance is maintained by a posture control mechanism the goal of which is to maintain the orientation of the body upright and thereby the center of mass (COM) above the base of the foot support. The maintenance of body uprightness during external stimuli is controlled mainly by a sensory negative feedback mechanism (Johansson, 1991), which involves cues from visual, vestibular and ankle angle proprioceptive receptors (Horak, 1996). Recent work that investigated the postural responses of normal subjects and vestibular loss subjects to body support motion and visual scene motion has shown that the system can, in fact, be described by a simple multisensory feedback model (Mergner, 2003). Furthermore, postural responses to external force stimuli in the form of pull were described by means of a multisensory feedback model (Mergner, 2003).

Mergner and his colleagues in Freiburg have achieved profound results in understanding the posture control mechanism from a system-theory point of view. They identified the main sensors involved, proposed a sensor-fusion-strategy explanation, and suggested a control hierarchy (Maurer, 2005). Clinical observations and results of experiments with normal subjects and neurological patients agreed with those obtained by simulation using the developed “technical” model.

2 CONTROL PROBLEM AND EXPERIMENTAL SETUP

The aim of neurological studies in posture control is to understand the existing control processes and the

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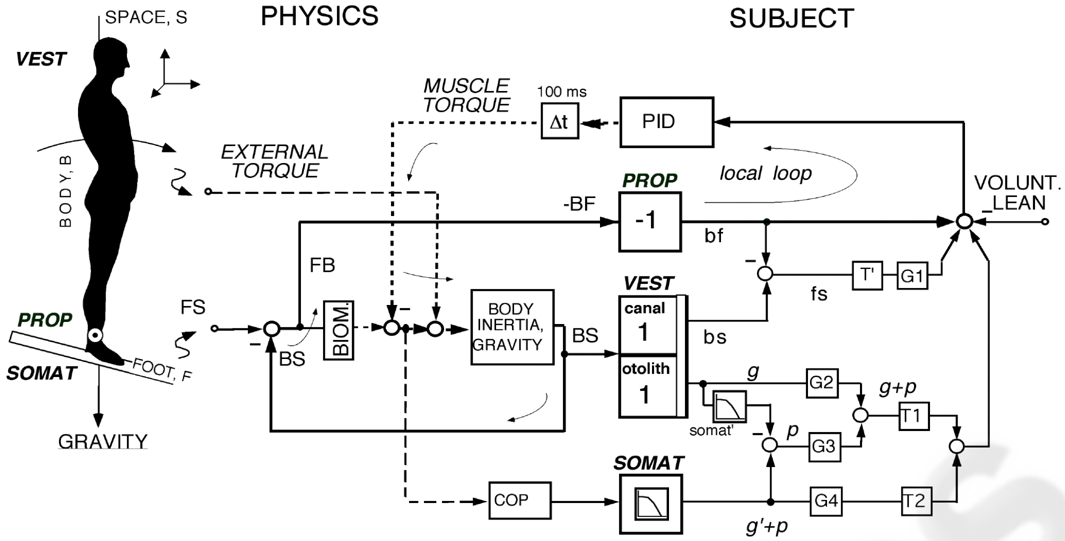

Figure 1: Multisensory model of posture control (from [3], slightly modified). The inset defines the 'PHYSICS' part of the model (left) in terms of an 'inverted pendulum body' (one segment for head, trunk, and legs) that pivots about the ankle joint on a potentially rotating platform (axis through the ankle joint). Pull on the body yields an 'external torque' stimulus acting on the body, which indirectly adds to the 'muscle torque' at the ankel joint. FS, foot-in-space angle (resulting from platform tilt); FB, foot-to-body angle (equal to -BF); BS, body-in-space angle). Box BIOM (for biomechanics) represents the transformation of FB into ankle torque (in the present case passive viscous–elastic properties are assumed to be very small as compared to external and muscle torques). Subjects' anthropometric parameters are contained in the box 'BODY INERTIA, GRAVITY'. Dashed lines represent torque and solid lines angles. All delays in the system are represented as one dead time (Δt). Ankle torque leads to a shift of the COP (box COP). The 'SUBJECT' part of the model (on the right) establishes internal representations of the external stimuli (torque from gravitational and external pull on the body, and FS angle), which are fed as set point signals, together with a voluntary signal (VOLUNT. LEAN), into a local proprioceptive negative feedback loop for body-on-support control (loop indicated by thin arrows). PROP, proprioceptive sensor; VEST, vestibular sensors (consisting of canal and otolith parts); SOMAT, plantar pressure cue ('somatosensory graviceptor'; low-pass frequency characteristics, corner frequency 0.8 Hz); somat', internal model of SOMAT; bf, bs, and fs, internal representations of BF, BS and FS, respectively; g, otolith-derived internal estimate of gravitational pull (g', somatosensory derived version of g); p, internal estimate of external pull; T1, T2, and T', detection thresholds; G1–G4, gain of set point signals (on the order of 0.7–0.9; held constant for all simulations of the results of normals).

causes of known abnormalities. This includes the identification of sensory systems and components, the sensor fusion process, the control architecture and subsystem, and the actuators. Recently, there has been an effort in quantizing this medical knowledge (or theories) in terms of a mathematical description (van der Kooij, 2001). It is evident that the aim of these studies is not to design but to analyze and understand the behavior of the system. The behavioral scenario should not only comprise small body excursions but also volitional action (voluntary body lean) in the presence of external perturbations (force field, gravity; contact force, pull on the body; motion of support surface, platform tilt). Superposition of all external perturbations should be allowed where stable performance is still anticipated.

A multisensory posture control model that demonstrates a nonlinear sensor fusion strategy (with some thresholds) and a PID controller (with saturation and time delay) is proposed by Mergner et al. (Mergner, 2003). Fig. 1 shows the whole architecture. In this model, three sensory systems are used; gains, time delay, and thresholds are derived from medical evidence. As to the model in its original form, neither the architecture (structure) nor the parameters were derived using any mathematical model or by any modern control theory technique. Yet, simulation results obtained by employing the model explained the medical observations including abnormalities in patients.

To avoid the difficulty in comparing simulation results with clinical results, a humanoid robot is pioneered (Fig. 2); it is built for the special purpose of addressing the posture control question. Its structure, dimensions, and parameters are selected in accordance with those known for human postural system. It is equipped with three sensor systems: vestibular system (involving a 3D accelerometer and a 3D gyrometer), joint-angle sensor (placed at the foot-ankle joint), somatosensory foot sole pressure receptors (for measuring COP shifts; this measure is equivalent to ankle joint torque). Furthermore, it is actuated with pneumatic actuators that generate forces of the same order as in humans. This humanoid is integrated to be the core of a hardware-in-the-loop simulation environment (Fig. 3.)

Figure 2: Photograph of humanoid robot 'PostuRob' standing on motion platform. Its aluminum skeleton consists of two rigid legs fixed to a pelvic girdle and a spine ('body'). Center of mass is mainly represented by two plumb weights on pelvis. Each leg carries a front and back 'muscle' to move the body with respect to the foot about the 'foot-ankle' joint.

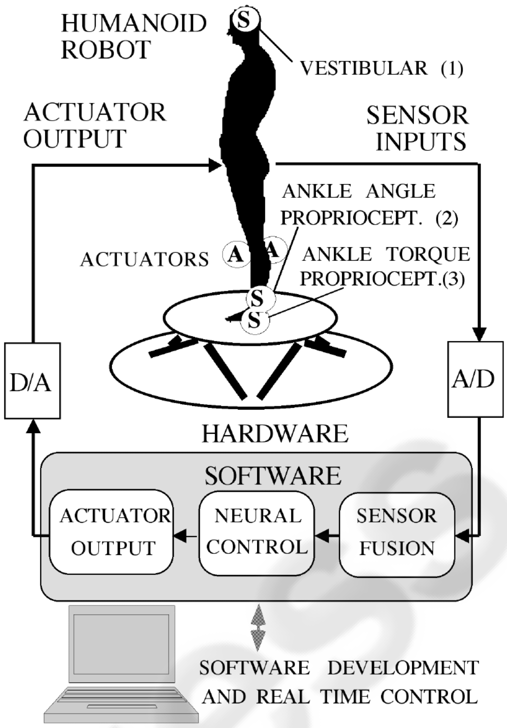

Figure 3: Hardware-in-the-loop simulation with actuators (A) and sensors (S).

3 CONTROL ENGINEERING APPROACH

A traditional model-based control approach is selected to tackle the posture control problem. The aim of the current study is to design a state and disturbance estimator as well as to design a controller that is capable of stabilizing the system and achieving desired voluntary motion even in the presence of the above mentioned disturbances. The control system is tested by using the humanoid robot model while taking the physical constraints (actuator saturation) in consideration. The ultimate goal of this part is not the control of the humanoid itself but the comparison with the human control. For this, the humanoid is modeled as two rigid bodies (the foot and the body) connected together with a revolute joint (foot-ankle joint) and actuated with pneumatic actuators (front and back sides) that apply forces on the body and reaction forces on the foot; the front and back forces produce the actuating torque. The foot rests on a movable platform (the same used for testing human subjects). Two foot reaction forces due to the weight and the dynamic forces can be measured by force sensors. Since the platform is allowed to tilt and external forces are allowed to pull the body, not only COP, but also a friction force between the foot and the platform is anticipated. The centers of mass of the foot and of the body are assumed to have some eccentricity from the vertical centerline passing through the joints. Fig. 4 shows the two rigid bodies, the actuators and the main acting forces. Experiments are designed to measure and identify the humanoid parameters as given in Table 1.

3.1 Modeling

The major forces acting on the humanoid are shown in Fig. 4. These include the reaction forces F_F and

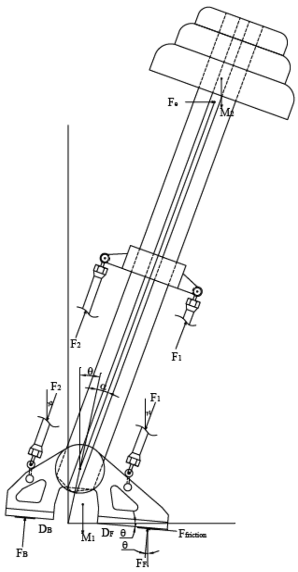

Figure 4: Main forces acting on the humanoid (drawing is not to scale).

Table 1: Humanoid Parameters.

Parameter	Meaning	Value	Unit
m_1	Mass of foot	8.6349	kg
m_2	Mass of body	90.724	kg
M_1	Weight of foot	84.7	N
M_2	Weight of body	890	N
D_F	Front force sensor distance to centerline of foot	0.1475	m
D_B	Back force sensor distance to centerline of foot	0.1025	m
h_1	Height of foot COM	0.0360	m
w_1	Eccentricity of foot COM	0.0121	m
h_2	Height of body COM	0.8500	m
w_2	Eccentricity of body COM	0.0018	m
h_a	Height of vestibular sensor set	0.8000	m
L	Distance to body COM	0.8500	m
d	Height of foot-ankle joint	0.1080	m
D	Distance from centerline to actuating force point of application	0.1000	m
D_c	Height from foot-ankle joint to actuating force point of application on body	0.4230	m
γ	Angle to body COM; ($\tan(\gamma) = w_2 / h_2$)	0.0021	rad

F_B , the friction force beneath the foot, the weight, the centrifugal and the inertia forces. Writing the motion equations for the two rigid bodies (the foot and the body) while assuming an external force F_e acting on the body and a tilting platform with angle θ and then canceling the internal reaction forces acting at the joint yields:

$$
\begin{aligned}
F_{friction} &= (M_1 + M_2)\sin(\theta) + F_e\cos(\theta) \\
&\quad - m_2\ddot{\alpha}L\cos(\alpha-\gamma) + m_2 L\dot{\alpha}^2\sin(\alpha-\gamma) \\
F_F + F_B &= (M_1 + M_2)\cos(\theta) - F_e\sin(\theta) \\
&\quad - m_2\ddot{\alpha}L\sin(\alpha-\gamma) - m_2 L\dot{\alpha}^2\cos(\alpha-\gamma) \\
D_F F_F - D_B F_B &= M_1(h_1\sin(\theta) + w_1\cos(\theta)) \\
&\quad + M_2 d\sin(\theta) + F_e d\cos(\theta) \\
&\quad - m_2 L d\,\ddot{\alpha}\cos(\alpha-\gamma) + m_2 L d\,\dot{\alpha}^2\sin(\alpha-\gamma) \\
&\quad + F_1\cos(\gamma_1)D - F_2\cos(\gamma_2)D \\
I_2\ddot{\alpha} &= -F_1 D + F_2 D + F_e(h_e - d\cos(\theta)) \\
&\quad + M_2 L\sin(\alpha + \theta - \gamma)
\end{aligned}
\tag{1}
$$

The variables notation is listed in Table 2. It is noted here that the effect of body motion appears in the reaction forces which can be measured. Further, the angle α is measured by the joint-angle sensor. Finally, the vestibular (accelerometer) sensor which is placed at the known height h_a provides two orthogonal acceleration quantities; these can be transformed to absolute coordinates to yield:

$$
\begin{aligned}
a_x &= g \\
a_y &= \ddot{\alpha}h_a + g(\alpha + \theta)
\end{aligned}
\tag{2}
$$

where g is the gravitational acceleration constant.

Table 2: Humanoid Variables.

Variable	Meaning	Unit
$F_{friction}$	Friction force between foot and platform	N
F_F	Measured reaction force at the foot front	N
F_B	Measured reaction force at the foot back	N
F_e	External pull force (disturbance)	N
F_1	Front actuating force	N
F_2	Back actuating force	N
α	Body angle relative to foot	rad
$\dot{\alpha}$	Body angular velocity relative to foot	rad/s
$\ddot{\alpha}$	Body angular acceleration relative to foot	rad/s^2
γ_1	Front actuator angle $\tan(\gamma_1) = \dfrac{D_c\sin(\alpha) + D(\cos(\alpha) - 1)}{D_c\cos(\alpha) - D\sin(\alpha)}$	rad
γ_2	Back actuator angle $\tan(\gamma_2) = \dfrac{D_c\sin(\alpha) + D(1 - \cos(\alpha))}{D_c\cos(\alpha) + D\sin(\alpha)}$	rad
θ	Platform tilt angle (external disturbance)	rad
h_e	Height of external pull force application point	m
a_x	Measured acceleration in the vertical direction	m/ s^2
a_y	Measured acceleration in the horizontal direction	m/ s^2

3.2 Estimation of External Disturbances

The main difficulties to control are the nonlinear dynamics as presented in the above equations and the presence of external disturbances that are not directly measurable. Since foot-ankle angle (and angular velocity), an acceleration at a known point, and reaction forces are measurable, then it should be possible to estimate these external disturbances including the pull force and the platform tilt. The estimation can be done either by solving the equations for the unknowns or by the means of an extended observer. The former option requires solving the nonlinear equations numerically as an analytical solution is difficult to obtain. The latter option can be realized after linearizing the dynamics.

3.3 Linearization

Since the voluntary motion is limited to a few degrees around the upright stance, the equations describing the dynamics of the humanoid can be linearized to yield:

$$\begin{aligned}
F_{friction} &= (M_1+M_2)\theta + F_e - m_2\ddot{\alpha}L \\
F_F + F_B &= (M_1+M_2) + m_2\ddot{\alpha}L\gamma \\
D_F F_F - D_B F_B &= M_1(h_1\theta + w_1) + M_2 d\theta + F_e d \\
&\quad -m_2 L d\ddot{\alpha} + F_1 D - F_2 D \\
I_2\ddot{\alpha} &= -F_1 D + F_2 D + F_e(h_e - d) \\
&\quad +M_2 L(\alpha + \theta - \gamma)
\end{aligned} \tag{3}$$

These equations which represent a linear time-invariant system can be expressed in state-space form as:

$$\begin{aligned}
\underbrace{\begin{bmatrix}\dot{\alpha}\\ \ddot{\alpha}\end{bmatrix}}_{\dot{x}} &= \underbrace{\begin{bmatrix}0 & 1\\ \frac{M_2L}{I_2} & 0\end{bmatrix}}_{A}\underbrace{\begin{bmatrix}\alpha\\ \dot{\alpha}\end{bmatrix}}_{x} + \underbrace{\begin{bmatrix}0\\ \frac{1}{I_2}\end{bmatrix}}_{B}\underbrace{D(F_2-F_1)}_{u} + \underbrace{\begin{bmatrix}0\\ \frac{M_2L}{I_2}\end{bmatrix}}_{H_1}\theta \\
&\quad + \underbrace{\begin{bmatrix}0\\ \frac{h_e-d}{I_2}\end{bmatrix}}_{H_2}F_e + \underbrace{\begin{bmatrix}0\\ \frac{M_2L}{I_2}\end{bmatrix}}_{H_3}\gamma
\end{aligned} \tag{4}$$

where the first part ($\dot{x} = Ax + Bu$) describes a linear system superimposed by the effect of external disturbances (θ, F_e, γ). Note that the eccentricity in the body COM (represented by γ) causes a tip over effect.

3.4 Control Law

Assuming that the external disturbances can be estimated, then their effect can be compensated by the control torque input u . Having done this, one obtains a simple linear system of second order for which the problem of robust tracking and disturbance rejection can be solved by the means of a classical PID controller. So, the control input u has two parts: the first u_d to compensate for the external disturbances while the second u_l to achieve desired closed-loop performance:

$$\begin{aligned}
u = &-\underbrace{(\hat{F}_e(h_e-d) + M_2L(\hat{\theta}-\gamma))}_{u_d} \\
&\underbrace{-(k_p\alpha + k_v\dot{\alpha} + k_i\textstyle\int(\alpha_d-\alpha)dt)}_{u_l}
\end{aligned} \tag{5}$$

where α_d is the desired "voluntary" body motion $\hat{F}_e$ and $\hat{\theta}$ denote the estimates of F_e and θ respectively. k_p, k_v, and k_i denote the position, velocity, and integral (robust tracking) feedback gains respectively. These gains are found by solving either a pole-placement or an optimal control problem. Since usually a voluntary motion is specified relative to an absolute frame (rather than relative to the platform), the summation of α and θ becomes the reference input. For this, the desired α_d is obtained by subtracting the estimated platform tilt angle $\hat{\theta}$ from the desired reference.

3.5 Extended Estimation

The linearized equation (4) can be rewritten in an extended form as:

$$\begin{aligned}
\underbrace{\begin{bmatrix}\dot{\alpha}\\ \ddot{\alpha}\\ \dot{\theta}\\ \dot{F}_e\end{bmatrix}}_{\dot{x}_e} &= \underbrace{\begin{bmatrix}0 & 1 & 0 & 0\\ \frac{M_2L}{I_2} & 0 & \frac{M_2L}{I_2} & \frac{h_e-d}{I_2}\\ 0 & 0 & 0 & 0\\ 0 & 0 & 0 & 0\end{bmatrix}}_{A_e}\underbrace{\begin{bmatrix}\alpha\\ \dot{\alpha}\\ \theta\\ F_e\end{bmatrix}}_{x_e} \\
&\quad + \underbrace{\begin{bmatrix}0 & 0\\ \frac{1}{I_2} & -\frac{M_2L}{I_2}\\ 0 & 0\\ 0 & 0\end{bmatrix}}_{B_e}\begin{bmatrix}u\\ \gamma\end{bmatrix}
\end{aligned} \tag{6}$$

where the external disturbances are considered as step-wise constant states. The five possible measurements can be collected in the form:

$$\begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ y_4 \\ y_5 \end{bmatrix} = \begin{bmatrix} \alpha \\ \dot{\alpha} \\ D_F F_F - D_B F_B \\ a_y \\ F_{friction} \end{bmatrix} = \underbrace{\begin{bmatrix} 0 & 0 \\ 0 & 0 \\ -(1+\frac{m_2 L d}{I_2}) & \frac{m_2 M_2 L^2 d}{I_2} \\ \frac{h_a}{I_2} & -\frac{M_2 L h_a}{I_2} \\ -\frac{m_2 L}{I_2} & \frac{m_2 M_2 L^2}{I_2} \end{bmatrix}}_{D_e} \begin{bmatrix} u \\ \gamma \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ M_1 w_1 \\ 0 \\ 0 \end{bmatrix} \tag{7}$$

$$+ \underbrace{\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ -\frac{m_2 M_2 L^2 d}{I_2} & 0 & M_1 h_1 + M_2 d - \frac{m_2 M_2 L^2 d}{I_2} & d - \frac{m_2 L d (h_e - d)}{I_2} \\ \frac{M_2 L h_a}{I_2} + g & 0 & \frac{M_2 L h_a}{I_2} + g & \frac{(h_e - d) h_a}{I_2} \\ -\frac{m_2 M_2 L^2}{I_2} & 0 & M_1 + M_2 - \frac{m_2 M_2 L^2}{I_2} & 1 - \frac{m_2 L (h_e - d)}{I_2} \end{bmatrix}}_{C_e} \underbrace{\begin{bmatrix} \alpha \\ \dot{\alpha} \\ \theta \\ F_e \end{bmatrix}}_{x_e}$$

It is straight forward to prove that the above system is observable with the measurements y_1 and y_2 together with any third measurement y_3, y_4, or y_5 or any combination of them. An estimator based on the above equation yields estimates for the states F_e and θ which are used in the control law(5).

3.6 Simulation Experiments

To test the validity of the above control and estimation strategy, a simulation experiment is designed. It is desired that the body moves voluntarily in the absolute space according to this function:

$$(\alpha+\theta)_{desired} = 3\sin(0.2\pi t) \tag{8}$$

in the presence of a tilting platform according to:

$$\theta = 3\sin(0.4\pi t) \tag{9}$$

and an external pulse pull force F_e with a magnitude of 30 N and a duration of 5 sec. Further, a time delay of $100ms$ is assumed at the controller-actuator side and a saturation of $100N.m$ is imposed on the actuator. At this end, the whole system comprised of the nonlinear plant, the extended estimator, and the robust tracking and disturbance compensator is built using the SIMLULINK environment. While the eigenvalues of the extended estimator are kept constant, different measurements are assumed. The estimator works well for all tested combinations. Figure 5 shows the actual disturbances and their estimates obtained by measuring α, $\dot{\alpha}$, and $D_F F_F - D_B F_B$. Both of the estimates match the actual disturbances very well except at the moment of applying the external force.

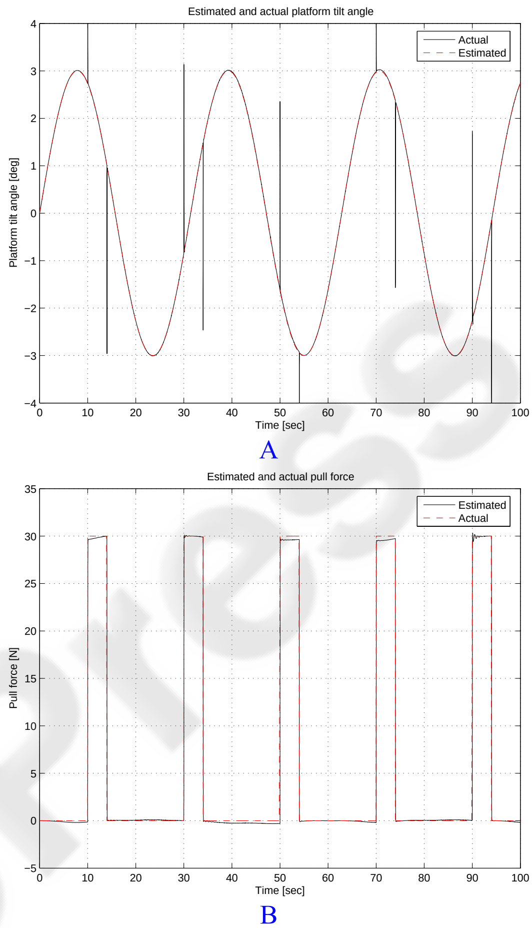

Figure 5: Actual and estimated external disturbances based on the measurement of α, $\dot{\alpha}$, and $D_F F_F - D_B F_B$. The estimated and actual platform tilt angle is shown in (A); the estimated and actual external pull force is shown in B.

The peaks observed in the estimate of the tilt angle are reduced when using the α, $\dot{\alpha}$, and a_y measurement and eliminated when using all measurements combined as shown in Figure 6.

In all cases the proposed control algorithm performs well in tracking the desired motion as shown in Figure 7 which corresponds to the configuration where only one measurement is used.

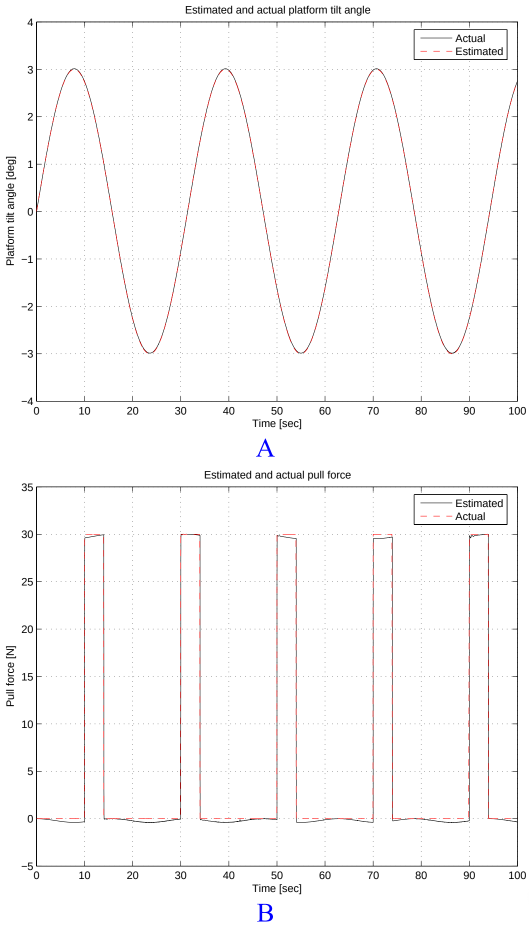

Figure 6: Actual and estimated external disturbances based on all measurements combined. The estimated and actual platform tilt angle is shown in (A); the estimated and actual external pull force is shown in B.

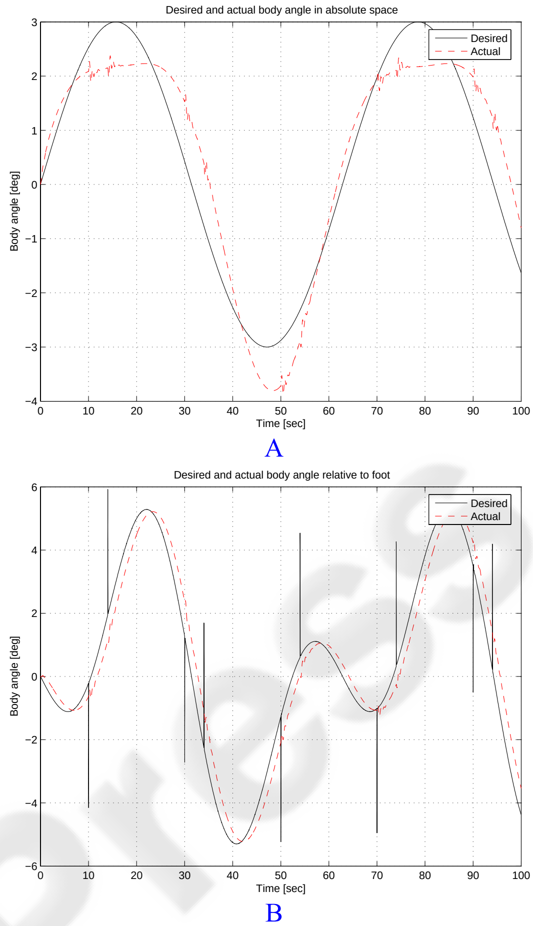

Figure 7: Simulation results for the humanoid with voluntary motion and external pull force in the presence of platform tilting. The external disturbances are found by the means of an extended observer that estimates both the states and the disturbances. Time delay of 100 millisecond is inserted between the controller and the actuator. The desired and actual voluntary motion in absolute space is shown in A; the desired and actual voluntary motion of the body relative to the foot is shown in B.

Finally, the effect of measurements noise is investigated. A white noise of about 10% of the signal is added to all measurements. The control system is proved to be robust against measurement noise especially the non-force measurements. However, it is noticed that the performance deteriorates when the force sensors become too noisy. Figure 8 shows simulation results at the presence of measurement noise assuming that all measurements are used. The proposed control strategy proves to be robust against sensor noise.

4 DISCUSSION, CONCLUSION, AND FURTHER WORK

The human posture control problem is studied from neurological and engineering perspectives. The aim of neurological studies is to analyze and understand the human posture control mechanism and to find models that are capable of explaining this behavior and its abnormalities. This has been the focus of dedicated medical and biological research groups. The results obtained by the workgroup in Freiburgfollowed the system engineering approach as mentioned in this paper. Although the methods applied by the neurological group do not follow in all respects the currently used approaches in control engineering, they still function very well and also explain abnormalities. A first attempt is made, in this article, to tackle the problem from a modern control engineering point of view. Thus, a model-

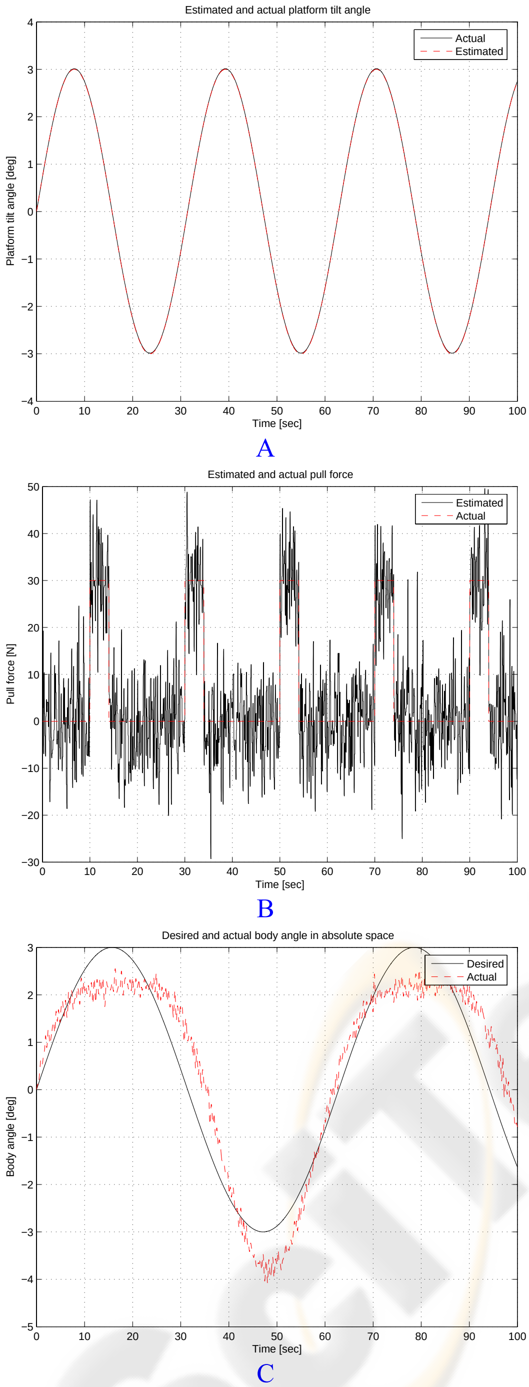

Figure 8: Actual and estimated external disturbances based on all measurements combined at the presence of sensor noise. The estimated and actual platform tilt angle is shown in (A); the estimated and actual external pull force is shown in B; the desired and actual voluntary motion in absolute space is shown in C.

based approach is followed. A dynamic model for the special-purpose humanoid is derived, an external-disturbance estimation method is presented, and finally a control method to compensate for estimated disturbances, to stabilize the system, and to achieve desired voluntary motion is used. Simulation results are promising. From a pure engineering perspective, the following results can be briefly stated:

1. Currently, it appears possible to use only one measurement (in addition to the foot-ankle measurements) for the purpose of estimating the disturbances and for controlling the motion.
2. It becomes necessary to use more measurements in the presence of sensor noise especially affecting the force sensors.
3. It is more beneficial to the estimation process to use the foot-platform tangential contact force (friction force) rather than the sum of the vertical ones.
4. A linear controller can be used if the external disturbances are estimated and compensated for.

In the future, the following remaining legitimate questions should be tackled and answered:

1. How well does the presented method perform when applied to the real (robot) system?
2. What are the similarities and differences between the two presented models?
3. What is necessary to transform one model into the other?

Once these questions are answered, engineers can anticipate applying neurological knowledge in the field of human posture control to engineering application areas as humanoids and walking machines and vice versa.

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