Implementation of a Human Model for Head Stabilization on a Humanoid Platform

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Abstract—The neuroscientific research shows that humans tend to stabilize their head orientation, while accomplishing a locomotor task. In order to replicate head movement behaviors found in human walk it is necessary and sufficient to be able to control the orientation (roll, pitch and yaw) of the head in space. The described behaviors can be replicated by giving suitable references to the head orientation. Based on these principles, a model based on an inverse kinematics controller has been designed. In this paper we introduce implementation of the model on a humanoid platform. Along we present results of two sets of experiments performed to verify two aspects of the proposed model. The results prove that the model can be used to efficiently stabilize the head’s orientation.

I. INTRODUCTION

Recent neurophysiological studies suggest that the head-fixed reference frame in humans plays a major role in body motion planning and execution [1]. It seems to be the privileged reference system where all sensory information is integrated and where whole-body motion planning occurs. This is one of the key concepts of “The Sense of Movement” [2] and that could simplify significantly motion planning and execution in complex kinematic structures like humans.

In humans, the vestibular system, perceiving rotational velocities and linear accelerations, provides perception information of the head movements and postures relative to space and gravity. It provides proprioceptive signals for the sense of movement. The central nervous system uses this information to generate a unified inertial reference frame, centered in the head that allows whole-body coordinated movements and head-oriented locomotion [2].

Pozzo and colleagues were the first to study the head behavior during locomotion [1]. Their experimentation revealed that vertical position of the head is not constant during human walking. The head always moves up and down depending on the gait phase and rotates in the opposite direction from head translation along the vertical axis. Hirasaki and colleagues [3] showed that the head oscillates up and down from about 4 centimeters during slow walking (0.8 m/s) to about 10 in fast walking (2 m/s) and about 5 centimeters from left to right in average in walking speeds between 1.4 and 1.8 m/s. A compensating contribution of the head yaw allows counteracting for body yaw. The same behavior has been observed for the roll and the pitch rotation of the head [4].

The reflex which uses vestibular information to stabilize head orientation in space is called angular Vestibulo-Collic Reflex (aVCR). Keeping the head orientation fixed in space has some advantages: the gaze is kept fixed on a distant target without intervention of eye muscles, and if the accelerometers in the vestibular systems are kept aligned with the gravity vector the gravity-inertia ambiguity is reduced. In fact, looking more closely at the yaw and pitch data, we can see that even if the magnitude of the head rotation in global reference frame compared to that of the trunk is greatly reduced, they are not always stabilized accurately to zero: we notice a correlation between yaw and horizontal translation and in the same way between pitch and vertical translation. This kind of behavior can be explained if we suppose that the subject is looking at a fixed point located some (small) distance ahead of the nose [1]. When the head moves up in the vertical plane pitch must compensate this movement by pointing down, and vice-versa. The same behavior must be followed also in the horizontal-yaw plane if we want to keep the gaze stable on a point ahead. This kind of reflex, which uses vestibular information to move the head to maintain gaze on a point at a finite distance (and not parallel to itself as in aVCR) is called linear Vestibulo-Collic Reflex (IVCR in short). Contributions from IVCR grow as speed increases. At speed under 1.2 m/s aVCR dominates, while at speeds above 1.2 m/s IVCR is dominant [3]. Whether we want to stabilize the head in space or keep the head pointing at a fixed point, in both behaviors appears clear that the relevant degrees of freedom to be controlled are the angular ones. The behavior can then be implemented giving the suitable inputs to the controllers, zero in case of aVCR and some geometrically computable function of time for IVCR. Walk with direction changes has been examined in [4]. Turning movements of both small radius (50 cm) and large radius (200 cm) have been captured at various speeds. One of the findings of this research is that large radius turns are in fact a combination of small radius turns and straight walking. So it is sufficient to...
analyze and replicate the straight walking and small-radius turning. Considering small-radius turns, the main behaviors which are not present during straight walking and should be replicated are the yaw anticipation and roll anticipation. Analyzing the yaw data during turn, Imai in his work [4] shows that head yaw is controlled (as it follows a smoother trajectory than body yaw) but it is not stabilized around trajectory (heading) yaw as we could expect. Head yaw seems to anticipate heading and body yaw. In other words, subjects tend to rotate their head towards the direction of the turn before the turn actually begins. This kind of behavior is not generated by a feedback mechanism as it begins before the turn actually takes place. The roll is not stabilized to zero as it is during straight walking. There is an anticipatory component of roll in the direction of the turn (i.e. the head tilts towards the inside of the turning trajectory). The magnitude of this behavior, called roll anticipation, is not negligible: maximum roll is about 8° and there is a sustained roll component of approximately 5° during the most part of the turn [4]. This behavior, moving the head towards the interior of the curve, creates a stabilizing moment about the feet which helps maintaining balance during the turn (counteracting the outward weight shift caused by centrifugal force).

Considering this analysis, we can conclude that in order to replicate head movement behaviors found in human walk it is necessary and sufficient to be able to control the orientation (roll, pitch and yaw) of the head in space. The described behaviors can be replicated by giving suitable references to the head orientation. Based on these principles, a model of the head stabilization has been designed [5]. This model is based on an inverse kinematics controller, suitable for an implementation on a robotic platform.

From the robotic point of view there are some implementations of head stabilization model [6, 7, 8]. Yamada and colleagues [6] propose a method for the stabilization of the snake-like robot head based on the neck control. The aim of their controller is to reject the disturbance of the body on the head using a continuous model. Another work on the head stabilization implementation on a robotic platform is proposed by Santos and colleagues [8]. This work focuses on a controller which minimizes the head motion induced by locomotion. In particular, the head movement is stabilized using Central Pattern Generator and a genetic algorithm. The results on a Sony AIBO robotic platform show the head movement is not totally stabilized during locomotion. Another controller [7] for the head stabilization has been implemented on the Sony AIBO robot. This controller is based on a machine learning algorithm able to learn the compensation for the head movements when no stabilization mechanism is present.

In this work we propose an implementation on KOBIAN robot of a bio-inspired human model for the head stabilization [5]. The paper is organized as follows: in the next section we describe the model of head stabilization. In third section we describe the implementation on the robotic platform. In following section we describe the experimental set up. In fifth section we describe results of the experiments and close the paper with short summary and introduction of future plans regarding the research in section six.

II. HEAD STABILIZATION MODEL

The control of the head rotation during walking appears essential in order to keep a stable head centered reference frame. In this perspective, a model in which the head is stabilized is proposed. The model [5] we propose considers the trunk rotation as a disturbance and allows following an input reference head rotation, compensating the trunk rotation.

Three frames of reference are considered for the model: 1) the world reference frame $O = xyz$; 2) and the head frame, fixed to the head, 3) and the trunk frame, fixed to the trunk. The head frame is composed by a rotation matrix $w_H^R$ which describes the orientation of the head with respect to the world frame as well as by a matrix $t_H^R$ which describes the orientation of the head with respect to the trunk. The trunk frame orientation is composed by a rotation matrix $w_T^R$ which describes the orientation of the trunk with respect to the world frame. In this model, the matrix $w_H^R$ depends on the motion during walking and can be considered as an external disturbance which affects the $w_H^R$ matrix. The relation between these matrices is a composition of rotations:

$$w_H^R = w_T^R t_H^R$$

(1)

A controller using as feedback the actual absolute RPY angles of the head ($\psi, \phi, \theta$), was designed to track an arbitrary reference orientation in space (not relative to the trunk) using Roll, Pitch and Yaw angles. The controller is able to follow a reference orientation ($\psi^*, \phi^*, \theta^*$) spanning in the whole workspace of the head and reject the disturbance caused by trunk motion.

For the implementation of this controller we had to find a relation between the joint velocities and the time derivatives of the head’s RPY angles. We decided to use the spatial Jacobian. The spatial Jacobian of the head in an arbitrary configuration can be calculated using the rigid adjoint transform of the direct kinematics. It can also be computed by direct inspection.

The Jacobian can be used to build a controller which has a proportional term $k$ and a feed-forward term consisting of the derivative of the reference ($\psi^*, \phi^*, \theta^*$). We subtract a term consisting of the speed of trunk motion (disturbance) to compensate also for the trunk motion, because the composition of angular velocities is linear, unlike the composition of rotations. In order to obtain information about trunk motion, we can notice that, knowing the absolute orientation of the head $w_H^R$ and the orientation relative to the trunk $t_H^R$ we could estimate the rotation of the trunk,

$$w_T^R = w_H^R (t_H^R)^T$$

(2)

and then, by differentiation, we could obtain the time
derivatives of the trunk RPY angles which can be used to compute the estimation of trunk orientation angles \( \hat{\psi}, \hat{\phi}, \hat{\gamma} \) and their derivatives \( \dot{\psi}, \dot{\phi}, \dot{\gamma} \). The final control law becomes therefore (3)

\[
\begin{align*}
\dot{\nu} &= k (\nu^r - \nu) + \nu^r \cdot \nu^t, \\
\dot{\phi} &= k (\phi^r - \phi) + \phi^r \cdot \phi^t, \\
\dot{\psi} &= k (\psi^r - \psi) + \psi^r \cdot \psi^t.
\end{align*}
\]

(3)

The feedback controller is depicted in Fig. 1 and the symbols on the figure have the following meaning:
- \( \theta \) - denotes the vector containing the roll, pitch and yaw angles \( (\nu, \phi, \psi) \) of the present head orientation
- \( \hat{\theta} \) - denotes the vector containing the derivative of roll, pitch and yaw angles \( (\dot{\nu}, \dot{\phi}, \dot{\psi}) \) of the head orientation reference
- \( \theta^r \) - denotes the vector containing the roll, pitch and yaw angles \( (\nu^r, \phi^r, \psi^r) \) of the current head orientation
- \( \hat{\gamma} \) - denotes the vector \( (\hat{\psi}, \hat{\phi}, \hat{\gamma}) \) containing the estimates of roll, pitch and yaw angles of the present trunk orientation

The data available for the control are the current configuration of the joints and orientation of the head. The orientation is compared with the reference to compute the orientation error, while the joint configuration is used for forward kinematics calculation to obtain the trunk orientation.

III. IMPLEMENTATION ON THE ROBOTIC PLATFORM

A. Robotic platform KOBIAN

The platform used in this research is a humanoid robot KOBIAN (Fig. 2)[9]. It was built for research on human robot interaction. Its proportions and major dimensions were based on those of average Japanese adult female. It is 1.4m high and weights 62kg. The mechanical structure (Fig. 2b) comprises two 6 DoF legs, 2 DoF waist, 1 DoF trunk, two 7 DoF arms, two 4 DoF hands, 4 DoF neck and 7 DoF head, in total 48 DoF. The robot has a centralized control system with Half-size Single Board Computer (SBC) responsible for low level control of the motors, as well as the motion patterns generation. The computer is equipped with Pentium M 2GHz CPU running the QNX Realtime Operating System.

B. Head stabilization model implementation

Since the neck of the robotic platform we used for implementation has 4 DoF and the algorithm described in [5] was developed for 3 DoF structure, we modified the method to calculate the inverse kinematics of 4 DoF link, given RPY angles of the head. Since the link has 4 DoF and we only need to control 3 DoF, our system becomes redundant and there is no analytical solution of the
Jacobian. To solve this problem we generate Jacobian from transformation matrices of individual joints [10]. Then to solve the inverse kinematics we use the dumped least-square inverse method [11, 12]. It employs the pseudo-inverse of the Jacobian matrix with additional dumping factor allowing inversion of Jacobian matrix even in close proximity to the singular configuration.

In the current stage, to obtain the orientation of the head, we first read the present values from rotational encoders of all joints and then use the forward kinematics to calculate head’s roll, pitch and yaw angles.

The head control algorithm was implemented on top of the motion pattern execution algorithm. It is executed every 30ms, and following the procedure depicted on Fig. 3 calculates the reference velocities for neck joints. The value is then integrated, interpolated and executed in 1ms position control loop.

IV. EXPERIMENTAL SET UP

We performed a set of experiments verifying the algorithm’s effectiveness of decoupling an orientational movement of the head from rest of the body. For that purpose we considered two experimental scenarios. In both of the scenarios, the robot was performing straight forward walk. In the first scenario the head orientation reference was constant and equal to 0 for all three angles. It was approximation of the straight walk with gaze fixed on the object placed far away from the subject, where the head orientation is not dependent on the fixated point (aVCR). In the second scenario, we assumed that the robot is fixating on the virtual object which is close to the subject, thus enforcing a constant change and control of the head orientation (IVCR). In all of the experiments robot was performing forward walk with stretched knee phase and flat foot initial contact. The step length was 200mm, step width 180mm, step time 1s. In the single experiment the robot performed 8 steps.

In the first scenario we performed two sets of experiments. In the first one, the head stabilization control was turned off with all neck joints locally controlled with reference angles equal to 0. In the second one, the head stabilization was turned on and the head orientation reference was constant and equal to 0. In this case the reference angles to the neck joints position controller were sent from the head stabilization controller.

In the second scenario, we performed experiments in which the robot was constantly orienting the head towards virtual point in space. In order to calculate the head reference orientation, in each head stabilization control cycle we calculate the position of the head coordinate frame in the world coordinate frame. This is done with use of the forward kinematics. Next to calculate the desired orientation of the head we assume that the Y axis of the head centered coordinate frame stays horizontal, while the X axis crosses the origin of the head coordinate frame and the virtual goal point on which robot tries to fixate. With these assumptions we calculate the desired rotation matrix for the head reference coordinate frame with use of the equations (4) - (6):

\[
\begin{align*}
H_r^G &= r_G - r_H \\
x_{\text{goal}} &= H_r^G \\
y_{\text{goal}} &= \begin{bmatrix} -\sin(\alpha) \\ \cos(\alpha) \\ 0 \end{bmatrix} \\
z_{\text{goal}} &= x_{\text{goal}} \times y_{\text{goal}} \\
^WR_{\text{goal}} &= \begin{bmatrix} x_{\text{goal}} & y_{\text{goal}} & z_{\text{goal}} \end{bmatrix}
\end{align*}
\]

Where:

- \(r_G\) – is the vector from global coordinate frame to the goal point (see Fig. 4)
- \(r_H\) – is the vector from global coordinate frame to the origin of head’s coordinate frame
- \(H_r^G\) – is the vector from head’s coordinate frame to the goal point
- \(\alpha\) – is angle between projection of \(X\) axis of head reference coordinate frame on \(XY\) plane of global coordinate frame

The goal in the experiment was set to the position of the head of the robot standing in front of our research platform and was equal to \(r_G = \begin{bmatrix} 3.8 & 0.7 & 1.4 \end{bmatrix}^T\).
V. RESULTS

The robot’s head, while walking, is subjected to impulsive acceleration caused by strong impact generated during foot initial contact with the ground. The impact is strong enough to disturb the position control and cause the head orientation to deviate from the zero reference. The size of deviation is visible in the results from the walking experiment without the head stability control. The trajectories of pitch and roll angles are visible on Fig. 5 and Fig. 8, respectively.

A. Fixed orientation reference

This experiment tested the ability of the head stabilization control to compensate for the motion of the body and stabilize head orientation. The red line on Fig. 5 and Fig. 8 show trajectories of head’s roll and pitch with control on. The amplitudes of the motion are from 2 to 7 times smaller compared to the trajectories with only joint 0 position control. Thus, the results prove that the head orientation in sagital and coronal planes decrease significantly when using the control, compared to no control conditions.

B. Virtual point following

In this experiment we simulated the IVCR where robot
adjusts the head orientation depending on the head’s vertical and horizontal motion. Graphs on Fig. 7 show the head position from the goal point is 1.7 cm.

The better overview of experiment scenario is presented on Fig. 6.

VI. CONCLUSIONS AND FUTURE WORK

In the paper we elaborated on the problem of head stabilization control in humans and humanoid robots. We described control model developed based on the human motion capture data analysis and verified it on the robotic platform. The implementation of the algorithm was done on humanoid robot KOBIAN. To verify the performance of the control we performed two sets of experiments in two different scenarios, one simulating a VCR and one simulating an IVCR. Results from both of the experiments show significant improvement in stability of the head. The vibrations of the head decreased in forward walking. Also the control enabled the head to track any chosen point in space adapting to changes in vertical and horizontal position of the head. The results proved that the proposed control model can be used to stabilize the head of the humanoid robot during locomotion.

Since the accuracy of the forward kinematics method used in the experiments can be highly affected by compliance of the structure, in the next stage of the research we will employ the Inertial Measurement Unit (IMU) as source of feedback about the orientation of the head. Also, in the future we plan to quantitatively verify the performance of the algorithm in absolute position measurement system, like VICON motion capture system. Moreover we plan to evaluate the influence of the head stabilization on the stability of the visual image acquired from the on-board cameras and resultant simplification of the visual reconstruction of the environment.

VII. REFERENCES


