Towards a methodology for stabilizing the gaze of a quadrupedal robot

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Abstract. When a quadrupedal robot moves, the body and head pitch, yaw and roll, because of its stepping. This natural effect of body and head motion adversely effects the use of visual sensors embedded in the robot's head. Any object in the visual frame of the robot will, from the perspective of the robot, be subject to considerable unmodeled motion or slip. This problem does not affect mammals, which have vestibulo-collic and vestibulo-ocular reflexes that stabilize their gaze in space and maintain objects of interest approximately fixed on the retina. Our work is aimed towards constructing an artificial vestibular system for quadrupedal robots to maintain accurate gaze. This paper describes the first part of this work, wherein we have mounted an artificial vestibular system in a Sony AIBO robot.

1 Introduction

Robot locomotion has been studied using a wide range of wheeled and legged robots [3]. Although wheeled robots move quickly, they can only move on smooth terrain and lack the versatility of legged robots in handling rough terrain. As a result, there has been a concerted effort within the robot community to understand the motion of legged robots [11]. This is particularly true within the RoboCup community, where there has been considerable work on both the Sony AIBO used by the legged league [11, 12] with a long-term aim of developing sophisticated humanoid soccer players and a humanoid league [4].

When playing soccer, using AIBO robots, one aim is to maintain specific landmarks and the ball within the visual range of a camera [17], which is mounted in the robot's head. A number of mechanisms that move the head with the aim of keeping the relevant object in the visual frame have been implemented [6] by obtaining feedback from motor sensors. These implementations are not accurate representations of head position in space, resulting in considerable errors during tasks that make use of vision information, such as self-localization [18], navigation [7] and identification of the ball [21]. This, in turn, leads to non-optimal trajectories in adjusting robot motion towards the ball and in team coordination activities such as passing the ball.

Additional problems arise during actual motion of the robot. The head, in which the camera is mounted, will pitch, yaw, and roll as well as linearly accelerate because of that motion. The very fact that legged motion generates this kind of disturbance makes it difficult to keep the visual frame stable.

One approach to dealing with this motion of the camera is to accept the motion and use a Kalman filter to track objects in the visual frame[6]. Another approach is to move the head to compensate for the unwanted motion, guided not by the direct feedback from the motor sensors, but instead from a learned response to the motor sensors which indicates what the motion really is. Such an approach could be based either on the model-based method introduced in [19], or on the neural-network method of [13].

In our work, we take a different approach, hypothesizing that the estimation of landmarks and ball position could be significantly improved if we had *a priori* knowledge of the statistics and spectral content of head rotations and linear accelerations when the robot executes particular tasks. As a result, we set out to measure these accurately. In mammals, the vestibular system compensates and orients the head and body as it moves through space. The purpose of this paper is to describe an enhancement that we have made to an AIBO robot using an an artificial vestibular system that allows us to estimate these statistics and spectra during particular motions that are presently used to identify landmarks and the ball. To this end, we have augmented the AIBO with a system that mimics the inertial sensing mechanisms of the vestibular system of mammals — see [15] for review. In this paper, we show the considerable angular head perturbations that exist during robot motions. We derive the signals in terms of the Euler angles of head rotation so that these signals can be utilized in estimating the landmarks and ball in space, relative to the camera during the various head maneuvers and locomotion. Rotational head compensations for linear perturbations are more complicated [16] and beyond the scope of this paper.

2 Related work

A number of studies have utilized robot enhancement using similar principles associated with the vestibular system [10, 13]. One approach attached gyrosensors to a walking robot to reduce the shaking effect on the camera caused by the walk [10]. This was done by using a high resolution camera and cutting out a subimage. The subimage frame moved according to the rotations measured by the gyrosensors. Despite this enhancement, the sensors alone did not provide satisfactory image clarity and additional template matching was utilized to refine the image. Our work to define the statistical and spectral content of the head perturbation in space should help to define the corrections needed to reduce the errors in the visual processing of the landmark and ball images.

3 Robot modification for studying quadrupedal locomotion

For our investigation, we used a Sony AIBO ERS-210 robot. The ERS-210 is a quadrupedal robot that has has three perpendicular degrees of freedom (DOF) in the head. The three degrees of freedom makes it possible to study the 3D head motion in space.

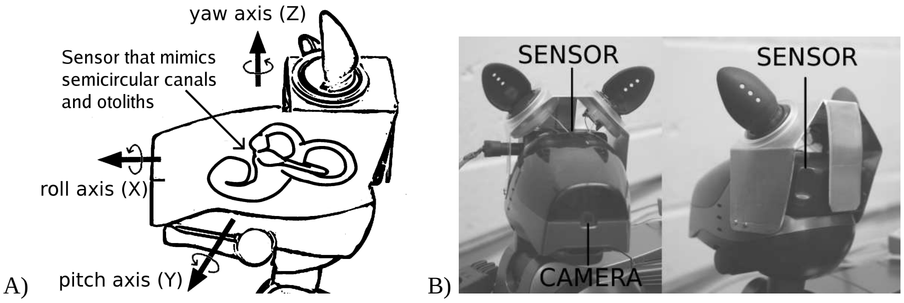

Fig. 1. A)Diagram of the head of an AIBO ERS-210 with embedded sensor mimicking the semicircular canals and otoliths. The heavy arrows show the roll (X), pitch (Y), and yaw (Z) axes of the head. The circular arrows indicate the positive direction of rotation. B) Modified AIBO ERS-210 that was used for these experiments, showing the sensor firmly mounted in the back of the head.

3.1 Sensor for measuring head perturbations

The AIBO has a linear acceleration sensor built into its body that can be used to obtain some useful data about its motion [20]. However, there is no accurate information about how the head moves. To establish information about the head, we used an Xsens MTX sensor[1]. This sensor is factory calibrated and can detect 3D linear acceleration $(\pm 17m/s^2)$ and 3D rotational velocity $(\pm 1200deg/s)$. This mimicks the peripheral vestibular system in live animals, which contains the semicircular canals and otoliths, structures that are embedded in the inner ear and sense angular and linear acceleration, respectively — see [15] for a review of work on the vestibular systems of humans and monkeys. The system of canals and otoliths is important for compensating and limiting head perturbations via the vestibulo-collic reflex as well as maintaining the stability of the visual world via the vestibulo-ocular reflex [15].

The sensor is $38 \times 53 \times 21mm$ and weights $30g$. Communication with the sensor is over an RS-232 interface to an off-board computer at a rate of $100Hz$ using a baudrate of $57.6kbits/s$. We have implemented an interface in Matlab 7 SP3[2] that runs on a Linux-based PC and can access signals from the sensor via Matlab. We have also implemented the matrix transformations that convert the rotary signals from the sensor into the Euler angular perturbations corresponding to the AIBO's head motor axes. The sensor was firmly embedded in the head of the AIBO at the approximate positions at which the peripheral vestibular system is located in the head of humans and other animals. This location is close to the origin of the axes of rotation of the head[3] (see Figure 1). As a result, the weight and displacement did not significantly alter the head's moment of inertia or its dynamic properties.

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[1] `www.xsens.com`

[2] `www.mathworks.com`

[3] Note that the ears of the AIBO are still attached despite the modification to the head of the robot. This was necessary since if the ears are removed, the AIBO will not boot up.

4 Relationship between robot head motors and the sensor

The AIBO has two coordinate frames: the body coordinate frame (BCF) and the head coordinate frame (HCF). The sensor is attached to the head so that its 3 axes correspond to the 3 axes of the HCF. The motors rotate the head with Euler angles defining a Helmholtz gimbal, i.e., the pitch axis fixed relative to the body [8]. The first motor performs a *pitch* of angle θ at the neck and moves the head, which contains the other two motors. The second motor performs a *yaw* of angle ϕ and moves the part of the head that contains the remaining motor. The last motor performs a *roll* of angle ψ and moves the final part of the head containing the sensor. Each rotation can be represented as a rotation around an axis:

$$roll = R_x(\psi) \qquad pitch = R_y(\theta) \qquad yaw = R_z(\phi)$$

The rotations may be combined in the proper order to create one pitch-yaw-roll rotation $R_{PYR} = R_x R_z R_y$ that defines the transformation from the BCF to the HCF.

4.1 Sensor reading

The sensor provides the 3D rotation velocity in space in terms of the head coordinate frame. Let us call this velocity ω_s. To convert this to Euler angles we need to determine the rotation of the head, add the incremental rotation caused by ω_s at time t, and determine what Euler angles would be the equivalent of such a rotation. Let $P_{cur} = [\psi_{cur}, \theta_{cur}, \phi_{cur}]$, equal to the original motor position. The original rotation matrix R_{cur} is obtained by inserting P_{cur}into R_{PYR} [8].

Any rotation in space may be represented by a single axis and a rotation angle. To obtain the axis of incremental rotation $\hat{n}_{inc}$, we need to normalize the velocity vector ω_s. To obtain the angle of incremental rotation $\varPhi_{inc}$, we multiply the magnitude of this vector by $\varDelta t$. In our case, $\varDelta t$ is the amount of time between sensor readings or $.01s$.

$$\hat{n}_{inc} = \frac{\omega_s}{\|\omega_s\|} \qquad \varPhi_{inc} = \|\omega_s\| \varDelta t$$

Now to obtain the new rotation, we simply apply the incremental rotation $R_{inc}(\hat{n}_{inc}, \varPhi_{inc})$ to the current rotation R_{cur} to generate R_{new}:

$$R_{new} = R_{inc} R_{cur}$$

From this matrix and the definition of the R_{PYR} matrix, we can extract the Euler angles of the new position P_{new}:

$$\psi_{new} = \tan^{-1} \frac{r_{32}}{r_{22}} \qquad \theta_{new} = \tan^{-1} \frac{r_{13}}{r_{11}} \qquad \phi_{new} = -\sin^{-1} r_{12}$$

The change of Euler angles is then $P_{new} - P_{cur}$. (See [14] for a complete derivation of these results.)

5 Experimental results and data analysis

We measured the positions as output by the external sensor and the internal motor sensors while the robot is walking. To generate the motion we utilized the motion module of the Carnegie Mellon University (CMU) team CMPack'04 from the 2004 RoboCup competition [5][4]. The robot gait utilized was the standard trot gait at the maximum forward velocity of $240mm/s$.

The test was run over a period of 8 seconds. The data were filtered by removing linear trends in position to remove the drift appearing in the external sensor readings. The resulting graphs are shown in Figure 2. The position information was then run through the Welch function available in Matlab to obtain power spectrums. The resulting graphs are shown in Figure 4. The averaged cycles were determined and are shown in Figure 3.

During walking at 240 mm/sec with a period of 640ms, the feedback from the external sensor shows considerable motion of the head in all three axis. The roll component of the head, which is approximately $6°$ peak to peak as reported by the vestibular sensor (Fig. 2 B) appears as less than $1°$ as reported by the motor sensors(Fig. 2 A). Similar strong discrepancies in rotation angles of the motor and vestibular sensor were found for pitch and yaw (Compare Fig. 2 C, E to Fig. 2 D, F).

We next considered how to best utilize the information in order to make corrections for the head movement. To accomplish this, we determined the average roll, pitch and yaw waveform during locomotion. The vestibular sensor determined clear periodic oscillatory patterns with small standard deviations around the mean (Fig. 3 B, D, F) whereas the motor sensors reported a negligible oscillation in all components of head movement.

The spectra of the comparable signals from motor and vestibular sensors were also significantly different (Fig. 4). The peak powers as reported by the external vestibular sensor were several orders of magnitude higher. The spectral content is also much narrower and more concentrated around the dominant harmonics in the vestibular sensor output as compared to the motor sensors. These are important parameters for determining the control that would be needed for optimizing compensatory head movements for maintaining head stability.

6 Conclusions

The results of this study indicate that all components of the head movements of an AIBO robot are periodic during locomotion. The spectra are fairly narrow and the average waveforms have small standard deviation over the period of movement. This indicates that the waveforms, as reported by the vestibular sensor, could form a basis for making corrections to images in camera coordinates and provide a stable platform for identifying objects of interest, including the ball and other robots.

We are currently working on using the readings to stabilize the visual frame of the AIBO. Initially we plan to add sensor feedback into existing approaches to gait development — for example [9] — delivering new gaits that exhibit better head stability.

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[4] This gait is a variation of the trot gait used by most RoboCup legged league teams.

Subsequently, we aim to have the AIBO respond in real-time, adjusting the head motors in response to detected head motion. Eventually, we plan to extend this work to humanoid robots. To our knowledge, there is currently no research on using vestibular feedback in gait development — despite the use of gyroscopic sensors [2] that provide similar information — nor is there any work on having robots dynamically adjust their gait to help stabilize head movement despite much work on gaits[1].

While RoboCup rules prevent us from using the modified AIBO in competition, we anticipate using the “head-stable” gaits we develop in future RoboCup events.

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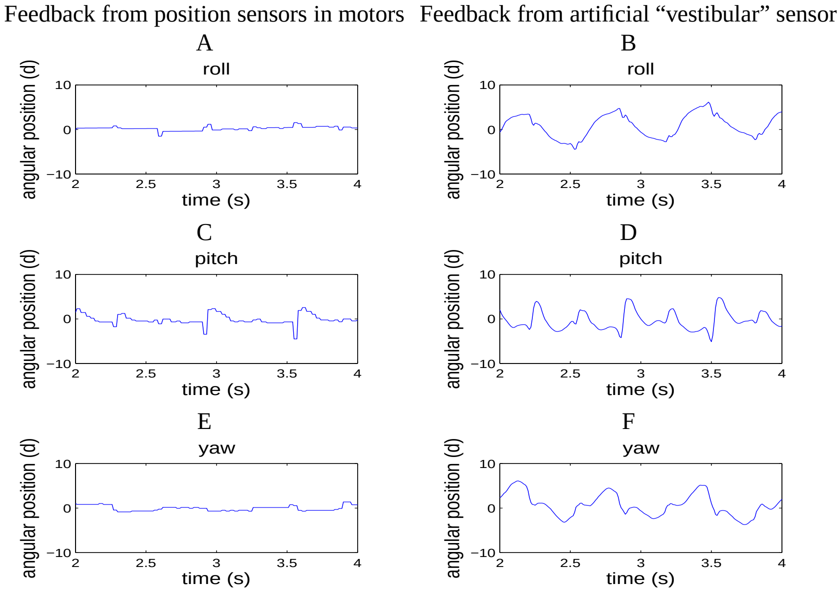

Fig. 2. Comparison of pitch,yaw,roll of the motor position sensors(A,C,E) and the artificial “vestibular” sensor(B, D, F) during walking

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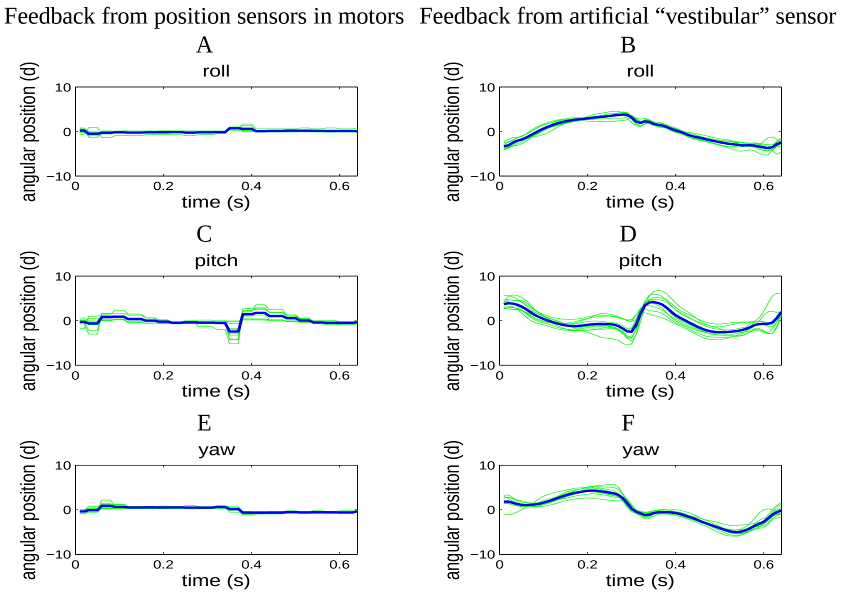

Fig. 3. Comparison of the average cycle of pitch,yaw,roll of the motor position sensors (A, C, E) and the artificial “vestibular” sensor (B, D, F) during walking

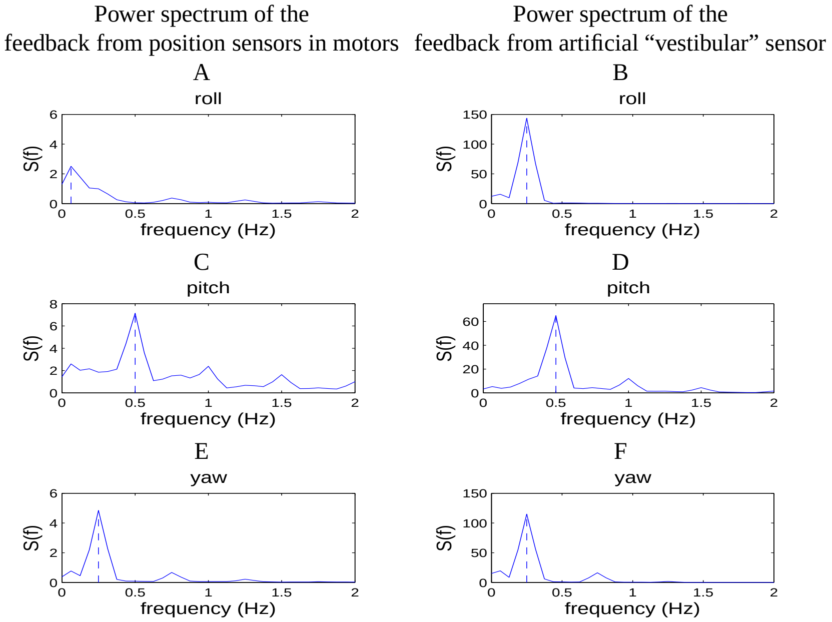

Fig. 4. Comparison of the pitch,yaw,roll power spectral density of the motor position sensors (A, C, E) and the artificial “vestibular” sensor (B, D, F) during walking. The peak frequency is .0625 for A, .25 for B, E, F and .5 for C, D.