An internal model of self-motion based on inertial signals.

S. Ramat, *Member, IEEE*, D. Pré, and G. Magenes, *Member, IEEE*

***Abstract*— The question of how the central nervous system can distinguish tilt with respect to gravity from inertial acceleration due to translation in a horizontal plane using vestibular information has long been debated by the scientific community over the past ten years. Recently, it was hypothesized that such discrimination may be based on the multisensory integration of information provided by the otolith organs and the semicircular canals. Some evidence of such processing was found in the neural activity of cells in the fastigial nuclei and vestibular nuclei. To investigate the ability of the central nervous system to build an internal model of self motion based on vestibular signals, we developed an artificial vestibular sensor composed of accelerometers and gyroscopes providing movement data of the same nature as that transduced by the otoliths and canals, respectively. Here we show that the processing of these signals based on the multisensory integration hypothesis can be successfully used to discriminate tilt from translation and that the internal model based on such processing can successfully track angular and linear displacements over short periods of time.**

I. INTRODUCTION

EINSTEIN'S Equivalence principle [1] implies that gravitoinertial accelerations due to translation or due to gravity cannot be distinguished by a linear accelerometer. Thus, an accelerometer cannot discriminate linear accelerations experienced during translational motion from gravitational acceleration due to changes in orientation with respect to gravity as experienced during tilt movements. In fact, recordings of primary vestibular afferents coming from the otolith organs in vertebrates show that the responses to linear accelerations and tilts with respect to gravity are equivalent as postulated by Einstein's principle [2-4]. Nonetheless, experimental evidence shows that the central nervous system (CNS) correctly discriminates tilt from translation and produces the appropriate vestibulo-ocular responses. This observation has interested the vestibular community for many years and two hypotheses have been proposed to explain how the brain might solve the tilt-translation ambiguity of the otolith organs. The "frequency segregation" hypothesis [5;6] states that the origin of the gravitoinertial acceleration measured by the otolith organs is deduced by the brain based on the frequency content of the otolith afferent signals. That is, low frequency accelerations are interpreted as tilt, while high frequency ones are interpreted as translations. The "multisensory integration" hypothesis [7-9] on the other hand states that the brain must use information coming from different sensors to build an internal model of self motion in space. Specifically, according to this theory, the discrimination of tilt and translation is accomplished by integrating angular velocity coming from the semicircular canals (SCC) and linear acceleration provided by the otolith organs.

In recent years, increasing evidence from behavioral experiments [10-12] has shown that the vestibulo-ocular reflex (VOR) discriminates tilt from translation primarily exploiting sensory information provided by the different vestibular organs, as postulated by the multisensory integration hypothesis. This was proved, for instance, by exposing subjects to interaural head translations, which evoked appropriately compensatory horizontal eye movements, and roll rotations about the naso-occipital axis, which elicited appropriate torsional eye movements [13;14]. Further evidence was provided by the recording of the neural activity of cells in the fastigial nuclei (FN) and in the vestibular nuclei (VN) [15;16]. Neurons in these areas were shown to fire accordingly to the computational steps that are required to compute the physical laws of motion to discriminate tilt and translation.

The mathematical model that is believed to be used by the brain to build the internal model of self motion exploits the angular velocity information provided by the SCC to keep track of the orientation with respect to gravity. That is, the brain integrates angular velocity to compute the traveled angle from the initial orientation following the equation:

$$\vec{g} = \int (\vec{g} \times \omega)dt \tag{1}$$

Therefore equation (1) allows to keep track of the direction of the gravity vector, which can be used to compute the acceleration due to translation from the gravitoinertial

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S. Ramat* (phone: +39-0382-985352; fax: +39-0382-985373; e-mail: steram@bioing.unipv.it), D. Pré (e-mail: pdebora@interfree.it) and G. Magenes (e-mail: giovanni@bioing.unipv.it) are with the Dipartimento di Informatica e Sistemistica, University of Pavia, 27100 Pavia, Italy

vector sensed by the otoliths by subtracting the gravity vector as in:

$$\vec{a}_{inertial} = \vec{a}_{recorded} - \vec{g} \quad (2)$$

And therefore by substituting equation (1) into equation (2) we obtain

$$\vec{a}_{inertial} = \vec{a}_{recorded} - \int (\vec{g} \times \omega) dt \quad (3)$$

While equation (1) may allow the brain to be aware of the orientation of the head, the estimate of the displacement in linear coordinates needs to be computed through the double integration of the inertial acceleration vector from equation (3):

$$s = \int (\int v dt) dt + s_0 \quad (4)$$

In order to quantitatively investigate how the CNS may compute an internal model of self motion allowing to discriminate tilt with respect to gravity from translation we aimed at reproducing the putative processing of the brain by using inertial signals relative to the same quantities provided by the sensory organs of the vestibular labyrinth, but acquired through an artificial sensor. To this goal we developed an artificial vestibular sensor using accelerometers and gyroscopes and used it to acquire experimental movement data. The acquired data was then processed in Matlab through an algorithm building the internal model based on inertial signals by implementing equations (1) through (4), as described in the Materials and Methods section. We finally compared the predictions of the internal model with a reference measurement made using a magnetic position sensor. We found that the reconstructed displacement and orientation, reproduced quite accurately the movement of the sensor over short periods of time (~2 seconds). The reconstructed movement would allow the brain to produce an ocular motor response compensating for the movement of the head over the first few hundred milliseconds, then other sources of information (e.g. visual after about 100 ms) become available and may be used to update the internal model.

II. MATERIALS AND METHODS

A. The ‘Vestibular’ sensor

In order to develop a sensor that would provide data containing the same sort of information as that transduced by the vestibular organs, we chose to combine linear accelerometers and angular gyroscopes. To this goal we used two, dual-axis, ±2g Memsic accelerometers (model MXA2312) which we mounted orthogonally on a square section aluminum tube, and three ±300°/s Analog Devices gyroscopes (model ADXRS300) that were mounted orthogonally to each other on the same aluminum support. An additional ±5g accelerometer is mounted along the z axis to ensure that reliable data is acquired even during falls or shock (e.g. during walking), that is when the acceleration may exceed ±2g. The resulting sensor is shown in Figure 1.

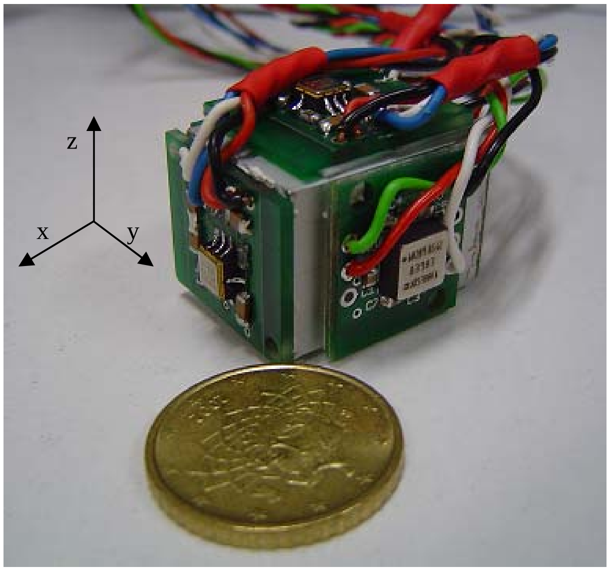

Fig. 1. The inertial sensor showing two accelerometers (left and top plate) and one gyroscope (right plate) is pictured together with a 50 Euro cent coin for size comparison.

B. Experimental paradigms

We defined three sets of paradigms implying rotations, translations and combined roto-translational movements to test our system. Each trials begins with at least two seconds during which the sensor is at rest, that are used to determine the initial orientation of the device. During pure rotation trials the sensor was mounted on a plastic bar at a distance of 20 cm from the center of rotation. The rotation was imposed either manually or using a servomotor controlled by the data acquisition computer. In the other trials the movement was imposed manually by the experimenter. The sensor signals were recorded at 120 Hz using a 16-bit data acquisition card controlled by a LabView program. The movement data was simultaneously recorded using a Fastrak system (Polhemus, Inc.) running at 120 Hz sampling rate. Such magnetic system records the three position and three orientation coordinates of a receiver with respect to a transmitter in 3D space. The latter signal is used as a reference position signal to compare with the results of our internal model algorithm.

C. Signal processing

The acquired data is low-pass filtered using a 15Hz Remez filter allowing very little ripples in both the pass-band and the stop-band. The initial conditions for the integration of the angular velocity are determined over the first two seconds of data through an optimization procedure that minimizes the following system of equations:

$$F(\theta,\varphi,\psi)=\begin{bmatrix}a_x\\a_y\\a_z\end{bmatrix}-R\begin{bmatrix}0\\0\\g\end{bmatrix} \qquad (5)$$

Here the three acceleration components (a) are those recorded by the accelerometers in the initial condition, R is the rotation matrix for Fick angles (yaw, roll, pitch) and g is the acceleration of gravity (9.81 m/s^2). The optimization procedure minimizes F by finding the three angles that represent the initial orientation of the sensor with respect to the Earth reference system.

The algorithm then tracks the orientation of the sensor by integrating the gyroscope signals working in the domain of quaternions, which, considering that data samples are ~8.3 ms apart, allows to avoid the problem of choosing an angle sequence convention (i.e. Fick, Helmoltz, etc.). The resulting orientation of the sensor defines the gravitational vector $\vec{g}$ that is used in equation (2). The displacement of the sensor is then computed by integrating twice the inertial acceleration vector according to equation (4).

III. RESULTS

Figure 2 shows the time based comparison of the output of the internal model with the displacement as recorded with the Fastrak system. The sensor was manually translated 40 cm on a horizontal plane along its y axis. The displacement estimated by the internal model is very close (sse=.015) to that recorded by the Fastrak system over the 2 seconds of data shown. For comparison, the figure also shows the result of integrating the raw sensor output along the same axis, i.e. before subtracting the resultant gravitational vector.

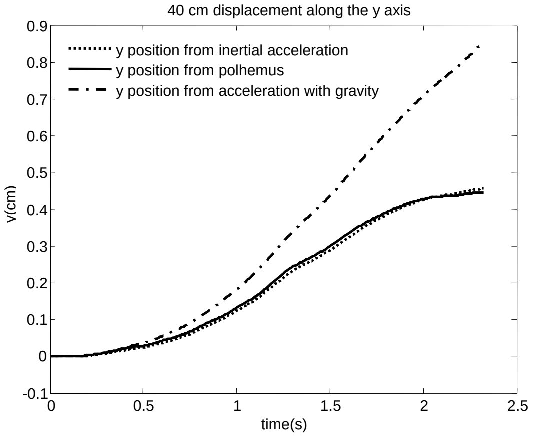

Figure 2. Comparison of the internal model estimate of displacement with the signal recorded with the Fastrak system during a 40 cm linear displacement of the sensor along its y axis.

The results of estimating the displacement of the sensor during planar motion (on the X-Y plane) along an arbitrary axis are shown in Figure 3, along with the data recorded using the Fastrak system and the results of integrating the raw signals from the sensor. The data is presented on the X-Y plane, thus time is not shown. The movement shown lasted about 1.9 s.

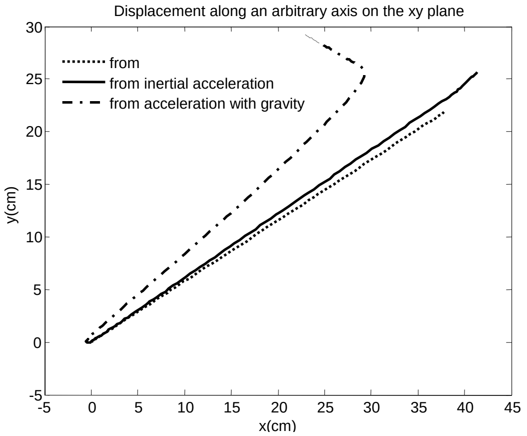

Figure 3. Comparison of the internal model estimate of displacement with the signal recorded with the Fastrak system during a linear movement on the sensor's X-Y plane.

Figure 4 shows the results of a pure rotational movement in the vertical plane from about 45 deg above the horizontal plane to about 20 deg below it, imposed manually.

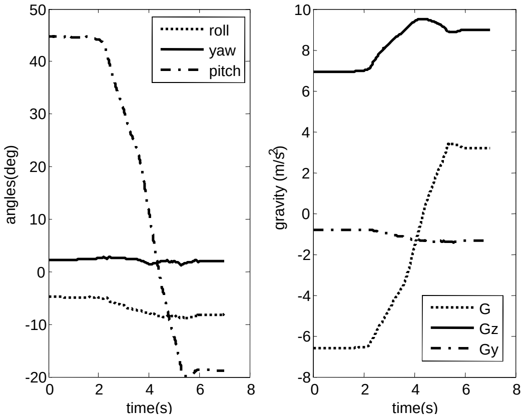

Figure 4. Example of rotational trial in the vertical plane. Left panel: rotation angles of the sensor. Right panel: internal model's estimates of gravity along the three axes of the sensor.

The data shown in the left panel illustrates the correct reconstruction of the rotation performed by integrating the angular velocity provided by the gyroscopes of the sensor. Correspondingly, the right panel shows the amount of gravity along the three axes of the sensor during the same movement. Gravity is initially partitioned almost equally among the x and z axes and as the sensor rotates it increases on the z axis peaking at about 1g as the sensor goes through the horizontal position. At the same instant in time the gravity sensed along the x axis goes through zero and then increases as the sensor becomes tilted downwards.

The accelerations sensed along the y axis remains close to 0 m/s^2 throughout the whole movement.

IV. DISCUSSION

The prototype system presented in this work was developed to study the sensory integration process that occurs in the brain based on linear acceleration information, including gravity and provided by the otolith organs, and on angular velocity information, provided by the SCC. Although the quality of the recordings using the artificial system may be improved by performing more accurate calibrations of the measuring devices, the results of the internal model algorithm are very encouraging.

The work presented here confirms that the multisensory integration hypothesis is suitable for the processing of vestibular information in order to build an internal model of self motion. The use of experimental data for testing the signal processing algorithm implementing the internal model allowed us to evaluate the suggested algorithm using real, thus intrinsically noisy, data. The results reported above show that the brain may use the estimates provided by such internal model over the first few hundreds of milliseconds, before the estimate deteriorates due to the integration of spurious noisy components of the data. By that time, though, movement information originating from other sensed would have become available to complement vestibular information. The brain may therefore use this slower but more reliable information to update the internal model continuously, following a weighted sensory integration concept.

V. CONCLUSION

The artificial sensor we developed together with its data processing program shows very promising results. We envisage that the system may be used in a multitude of applications ranging from inertial navigation systems, to robotics and measurement of human movements.

Bibliography

[1] Einstein, A., "Uber das Relativit¨atsprinzip und die aus demselben gezogenen Folgerungen," *Jahrb.Radioakt.4*, vol. 4 pp. 411-462, 1908.

[2] Fernandez, C. and Goldberg, J. M., "Physiology of peripheral neurons innervating otolith organs of the squirrel monkey. I. Response to static tilts and to long-duration centrifugal force," *J.Neurophysiol.*, vol. 39, no. 5, pp. 970-984, Sept.1976.

[3] Angelaki, D. E. and Dickman, J. D., "Spatiotemporal processing of linear acceleration: primary afferent and central vestibular neuron responses," *J.Neurophysiol.*, vol. 84, no. 4, pp. 2113-2132, Oct.2000.

[4] Anderson, J. H., Blanks, R. H., and Precht, W., "Response characteristics of semicircular canal and otolith systems in cat. I. Dynamic responses of primary vestibular fibers," *Exp.Brain Res.*, vol. 32, no. 4, pp. 491-507, Aug.1978.

[5] Paige, G. D. and Tomko, D. L., "Eye movement responses to linear head motion in the squirrel monkey. I. Basic characteristics," *J.Neurophysiol.*, vol. 65, no. 5, pp. 1170-1182, May1991.

[6] Telford, L., Seidman, S. H., and Paige, G. D., "Dynamics of squirrel monkey linear vestibuloocular reflex and interactions with fixation distance," *J.Neurophysiol.*, vol. 78, no. 4, pp. 1775-1790, Oct.1997.

[7] Mayne, R. A., "A systems concept of the vestibular organs.," in H.H.Kornhuber (ed.) *Handbook of Sensory Physiology Vestibular System, Part 2.* New York: Springer-Verlag, 1974, pp. 493-580.

[8] Ormsby, C. and Young, L. R., "Integration of semicircular canal and otolith information for multisensory orientation stimuli," *Math.Biosci.*, vol. 34 pp. 1-21, 1977.

[9] Merfeld, D. M., Zupan, L., and Peterka, R. J., "Humans use internal models to estimate gravity and linear acceleration," *Nature*, vol. 398, no. 6728, pp. 615-618, Apr.1999.

[10] Zupan, L. H., Peterka, R. J., and Merfeld, D. M., "Neural processing of gravito-inertial cues in humans. I. Influence of the semicircular canals following post-rotatory tilt," *J.Neurophysiol.*, vol. 84, no. 4, pp. 2001-2015, Oct.2000.

[11] Angelaki, D. E. and McHenry, M. Q., "Short-latency primate vestibuloocular responses during translation," *J.Neurophysiol.*, vol. 82, no. 3, pp. 1651-1654, Sept.1999.

[12] Hess, B. J. and Angelaki, D. E., "Oculomotor control of primary eye position discriminates between translation and tilt," *J.Neurophysiol.*, vol. 81, no. 1, pp. 394-398, Jan.1999.

[13] Angelaki, D. E., McHenry, M. Q., Dickman, J. D., Newlands, S. D., and Hess, B. J., "Computation of inertial motion: neural strategies to resolve ambiguous otolith information," *J.Neurosci.*, vol. 19, no. 1, pp. 316-327, Jan.1999.

[14] Angelaki, D. E., Wei, M., and Merfeld, D. M., "Vestibular discrimination of gravity and translational acceleration," *Ann.N.Y.Acad.Sci.*, vol. 942 pp. 114-127, Oct.2001.

[15] Angelaki, D. E., Shaikh, A. G., Green, A. M., and Dickman, J. D., "Neurons compute internal models of the physical laws of motion," *Nature*, vol. 430, no. 6999, pp. 560-564, July2004.

[16] Angelaki, D. E. and Dickman, J. D., "Gravity or translation: Central processing of vestibular signals to detect motion or tilt," *J.Vestib.Res.*, vol. 13, no. 4-6, pp. 245-253, 2003.