# Bio-inspired Implementation of Linear Vestibulo-Ocular and Opto-Kinetic Reflexes in a Humanoid Robot

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***Abstract*** *— The vestibulo-ocular and opto-kinetic reflexes (VOR and OKR) in primates combine to provide compensation for head rotation and translation in space to maintain a steady visual field on the retina. We previously implemented an artificial angular vestibulo-ocular reflex (aVOR) in a fully articulated binocular control system of a quadruped robot head.[1] We extend our work by introducing a linear component of a vestibulo-ocular reflex (lVOR) to provide image stabilization during linear perturbations of the head. The proposed algorithm fuses visual and vestibular sensors to provide long-term bias stability and fast transient response under a wide frequency range. We implement and test the algorithm in a biped robot by perturbing quiet stance with transverse sinusoidal movements of a linear sled. Retinal slip information obtained from the stereo camera pair simulating the OKR, provides the measure of efficacy of the combined algorithm.*

## I. INTRODUCTION

A custom-designed humanoid head was fit with servo actuators that comprise a 9 Degree of Freedom (DOF) system. The neck has 3DOF and each Ocular Servo Module (OSM) has 3DOF with three orthogonal servo motors functioning similarly to the eye muscles. The vestibular system (inertial sensor) outputs angular velocity and linear acceleration in a right handed coordinate frame. A cascade of acceleration-velocity and a velocity-position integrators transform these signals into a linear displacement vector used to compute the compensatory rotation commands for the OSM. High sampling rate ($f_{VOR}$=120Hz) of an inertial sensor, comprising the VOR minimizes phase lag between high frequency transients and compensatory response, while optical flow computation of the OKR resets the accumulated bias of the VOR to provide long term bias stability in the low-frequency range of excitation ($f_{OKR}$=15Hz).

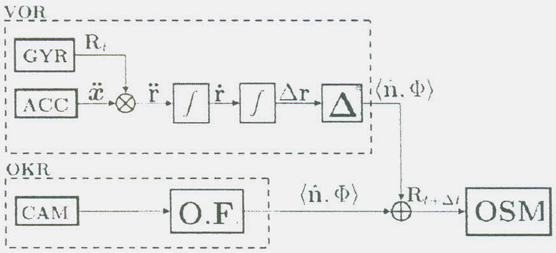

**Figure 1** VOR/OKR system outline

## I. VOR MODEL

At time t, the orientation of the head is given by

$$\mathbf{R}_t = \mathbf{R}_z(\theta)\mathbf{R}_y(\varphi)\mathbf{R}_x(\psi) \qquad (1)$$

where $\theta, \varphi, \psi$ are Euler angles representing yaw, pitch and roll within the Fick gimbal. Following an external perturbation, in the interval between $t$ and $t + \Delta t_{OKR}$, the head undergoes simultaneous linear and angular displacements measured in the inertial sensor's reference frame. At each time step $\Delta t_{VOR}$, the acceleration vector $\ddot{x}$ is projected onto the world coordinate frame and integrated twice to obtain a relative linear displacement $\Delta\mathbf{r}$ given by

$$\int\int\left(\mathbf{R}_t\frac{d^2\mathbf{r}_t^T}{dt^2}+\epsilon^T\right)dt^2 \qquad (2)$$

where $\epsilon$ is a bias term largely attributed to a residual projection of the gravity vector due to the imprecision of the gyroscope. As a result, error in the estimated displacement grows quadratically, but remains <10 mm within $\Delta t_{VOR}$. A linear displacement $\Delta\mathbf{r}$ in the world reference frame generates angular displacement of the visual target $\mathbf{P}$ in the camera reference frame, requiring an incremental compensatory rotation through angle $\Phi$ about an axis $\hat{\mathbf{n}}$ normal to the plane containing $\mathbf{r}_t$ and $\Delta\mathbf{r}$ given by $\mathbf{r}_t \times \Delta\mathbf{r}$ (Fig. 2). At instance $t + \Delta t_{VOR}$, a compensatory rotation matrix $\mathbf{R}_{inc}$ is computed by Rodriguez Formula [1], to obtain the updated orientation $\mathbf{R}_{t+\Delta t}$ given by $\mathbf{R}_{inc}\mathbf{R}_t$. The updated Euler angles of the eye motors are extracted from $\mathbf{R}_{t+\Delta t}$ and fed into the OSM to reposition the cameras.

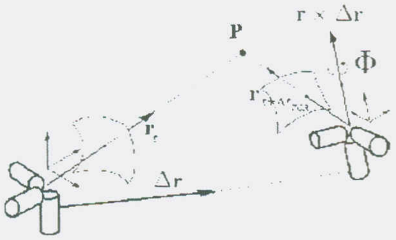

**Figure 2** VOR computation of compensatory rotation

## II. OKR MODEL

The OKR is modeled as an optical flow field $\mathbf{F}$ consisting of a linear combination of background and foreground fields. Sparse optical flow is computed using Lukas-Karanade algorithm for a set of feature vectors $I$ selected using a Harris operator. The background field is assumed to be at infinity and independant of linear petrubations of the head. A feature subset $I_b \subset I$ is modeled as a background field $\mathbf{F}_b$ and is given by

$$\begin{pmatrix} \delta x \\ \delta y \end{pmatrix} = \begin{pmatrix} -k(y - y_0) + u_x \\ k(x - x_0) + u_y \end{pmatrix} \tag{3}$$

where $k$, $u_x$, $u_y$ are proportional to roll, yaw and pitch components of $\hat{\mathbf{n}}$ repectively. A foreground field is given by $\mathbf{F}_f = \mathbf{F}_b + \mathbf{u}$, where $\mathbf{u}$ is a vector in the image coordinate frame proportional to the linear displacement $\Delta\mathbf{r}$ in the world coordinate frame. At time $t + \Delta t_{OKR}$, model parameters are estimated using a Random Consensus (RANSAC) algorithm to compute compensatory angle and axis of rotation and reset the accumulated bias of the VOR.

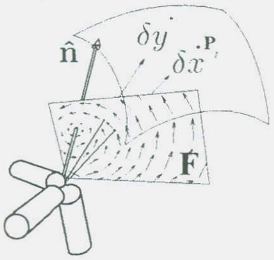

**Figure 3** OKR computation of compensatory rotation

## III. RESULTS

To test the lVOR system, the robot was accelerated on a linear sled while in quiet stance and oriented in the direction of a visual target. The robot was offset 1m from the projected target, and the platform accelerated sinusoidally in place with amplitude of 10cm. The response was obtained by implementing OKR and lVOR together, and separately, at various frequencies ranging between 0.05Hz and 3 Hz. Several important characteristics of the system can be observed from the time-domain plots of the response. First, the OKR response alone is incapable of suppressing the oscillations fast enough without a significant phase shift. Because the OKR is processed at one tenth the rate of the VOR, significant delay of the response of the motor is expected when OKR is implemented alone at frequencies above 0.2 Hz. Integrating lVOR and OKR provides additional bandwidth (120Hz) to reduce delay and attenuate the unwanted response. Thus, compensatory motor commands due to the lVOR and OKR optimize both transient and steady-state response.

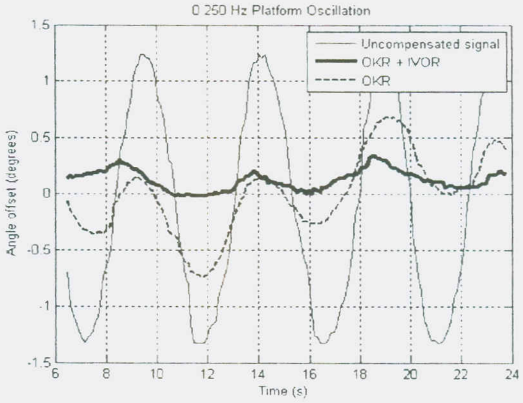

**Figure 4** Time domain response of VOR/OKR

## IV. REFERENCES

[1] R. Kaushik, M. Marcinkiewicz, J. Xiao, and T. Raphan, "Implementation of Bio-Inspired Vestibulo-Ocular Reflex in a Quadrupedal Robot," in *International Conference on Robotics and Automation*, Roma, Italy, 2007, pp. 4861-4866.

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[3] Y. Hirata, and S. M. Highstein, "A Dynamic model for the vertical vestibuloocular reflex and optokinetic response in primate," in *Neurocomputing*, Atlanta, GA, 2003, pp. 531-540.