The Kinematics and Eye Movements for a Two-Eyed Robot Head

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Abstract

This paper is part of a study of gaze control for a two-eyed robot head. The kinematics of the head and eye movement planning for the subcontrols loosely corresponding to saccade, pursuit, VOR(vestibulo-ocular reflex), OKR(opto-kinetic reflex), and vergence are presented.

1 Kinematics

The gross structure of the robot head and the coordinate frames are shown in figure 1. There are four degrees of freedom, i.e., pan, tilt, and left and right vergence joint. In the figure, P is the fixation point. θ_h is the pan angle. The inter-ocular separation is B. The ray from ${}^eO$ to P makes gaze angle α with ${}^eX$. θ_r and θ_l are the vergence joint angles. a is the distance between origin of e(eye) frame and s(system) frame. The tilt angle is denoted θ_t. Assume that the fixation point position and its velocity vector are ${}^sX_a$ and ${}^sV_a$ in s frame, we find:

$$ {}^sX_a = \mathbf{F}_1(\Theta); \quad {}^sV_a = J(\Theta) * \Omega \tag{1} $$

where $F_1(\cdot)$ is a set of nonlinear functions, $\Theta = \{\theta_r, \theta_l, \theta_h, \theta_t\}^T$ is the joint position vector of the head, $\Omega = \{\omega_h, \omega_t, \omega_r, \omega_l\}$ is the joint velocity vector of the head, and J is the 3×4 Jacobian matrix,

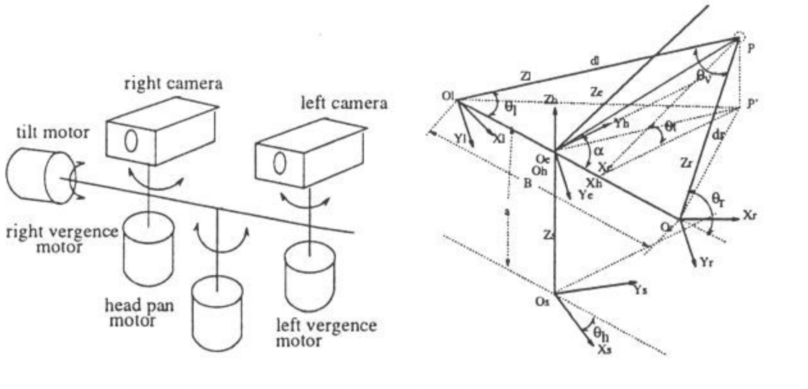

Figure 1: The structure of the robot head and its coordinate frames

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2 Inverse Kinematics

If we want the head to fixate on the object at ${}^sX$, i.e., to maintain the image of the object at the center of the left and right image planes, we obtain only three constraints. For our robot head, in order to obtain unique solution, further constraint must be added. If we propose to maintain the eyes in their most "comfortable" positions. We find:

$$\Theta = \mathbf{F}_2({}^sX) \tag{2}$$

If the head pan angle θ_h is held stationary for a new fixation, we obtain: (Θ_1 is composed of the last three components of Θ):

$$\Theta_1 = \mathbf{F}_3({}^sX, \theta_h) \tag{3}$$

Suppose that the velocity of the object of interest in the system frame is ${}^sV$. If we want to track it, the following relationships must hold (J^+ is the pseudoinverse of the Jacobian matrix):

$$\Omega = J^+ *^s V \tag{4}$$

3 Eye movement planning

3.1 Vergence

Suppose that the relative retinal disparity of the image of the object in the X direction of the image plane is μ_x. If the system tries to keep the "eyes" in their most "comfortable" position, vergence planning process is listed in table 1.

Table 1: The vergence planning and suitable conditions

scheme	planning	condition
changing left	$\delta\theta_l = \frac{\mu_x}{f_l}$	($\alpha > 90°$ and $\mu < 0$) or ($\alpha < 90°$ and $\mu > 0$)
changing right	$\delta\theta_r = -\frac{\mu_x}{f_r}$	($\alpha > 90°$ and $\mu > 0$) or ($\alpha < 90°$ and $\mu < 0$)
changing both	$\delta\theta_r = -\frac{\mu_x}{2f_r}$ $\delta\theta_l = \frac{\mu_x}{2f_l}$	gaze angle is approximately 90°

3.2 Saccade

Assume that the new point of interest is ${}^sX$, the desired state of the head to achieve a saccade can be computed from equation 2 or 3. There are an infinite number of solutions according to the different head pan positions. Among these, three are most interesting: (a) *keeping the head pan angle fixed saccade* (using motion other than head pan to achieve the saccade); (b) *keeping gaze angle 90° saccade* (maintaining the gaze angle 90° during a saccade); (c) *full motion saccade* (using all the joints simultaneously to achieve a saccade). Saccade must take care of three situations: (i) *simple saccade*. The head makes a saccade from a stationary state to a stationary object. (ii) *saccade followed by tracking*. (iii) *saccade after tracking*.

3.2.1 Simple Saccade

For *keeping the head pan angle fixed saccade* and *keeping gaze angle* 90° *saccade*, we can obtain the motion vector use equations 2 or 3. Using bang-bang or bang-coast-bang motion, the saccade can easily be planned. For a *full motion saccade*, path planning is more complicated.

For $\theta_h \in \{\theta_{h\_now}, \theta_h^d\}$ or if $\theta_{h\_now} > \theta_h^d$, $\theta_h \in \{\theta_h^d, \theta_{h\_now}\}$, from equation 3 we can obtain:

$$\theta_t = f_1(\theta_h, {}^sX); \quad \theta_l = f_2(\theta_h, {}^sX); \quad \theta_r = f_3(\theta_h, {}^sX) \tag{5}$$

where ${}^sX$ is the target of the saccade and f_i is a nonlinear function. Assume that the motion time for the head pan is t_h for a θ_h and the corresponding motion time for other joints are t_t, t_l, t_r respectively. The above equations can be rewritten as:

$$t_t = F_1(t_h, {}^sX); \quad t_l = F_2(t_h, {}^sX); \quad t_r = F_3(t_h, {}^sX) \tag{6}$$

These equations are highly nonlinear, so optimal search for a minimum time saccade is difficult. We use instead a suboptimal solution, see [2]:

3.2.2 Saccade followed by tracking

Assume that the position and the velocity of the object of interest are ${}^sX$ and ${}^sV$, and that the fixation point is ${}^sX_a$. If the time required to complete the saccade is δt, the desired velocity of fixation point should be: ${}^sV_d = {}^sV + \frac{{}^sX - {}^sX_a}{\delta t}$. Using equation 1, this saccade can be planned. In real system, because of the maximum velocity limits of the joints, above equation is used only to find a motion direction which can reduce the position error.

3.2.3 Saccade after Tracking

This is the same as the simple saccade except that the initial joint speed of the head is not zero. It can easily be planned use the similar method as simple saccade, see [2].

3.3 VOR

In our approach, VOR is redefined as the process of adjusting the head pan angle so that the "eyes" can maintain their most "comfortable" position, i.e., to keep the gaze angle near to 90°. Assume that the current pan angle is θ_h^0, and that the pan angle required to achieve 90° gaze angle is θ_h^d. The head pan speed to achieve VOR can be given by:

$$\omega_h = k_h * (\theta_h^d - \theta_h^0) \tag{7}$$

To reduce the difficulties of implementation, this equation can be replaced by:

$$\omega_h = k_h * (\theta_l^0 + \theta_r^0 - 180°) \tag{8}$$

where k_h is a constant. Known ω_h, VOR planning is straightforward using the planning method discussed in section 3.4.4.

3.4 Pursuit

Assume that the object of interest is at ${}^sX$ and moving with velocity ${}^sV$. The position of the fixation point is ${}^sX_a$. For the head to track the object, the velocity of the fixation point must satisfy:${}^sV_d = {}^s V + \frac{{}^sX - {}^sX_a}{\delta t}$ (δt: sample time). Using different constraints, different pursuit schemes can be planned.

3.4.1 Full motion tracking

If we want to use all the joint simultaneously to achieve tracking, equation 1 can be used to planned the motion.

3.4.2 Tracking while holding the head pan angle fixed

If the movement of joints other than head pan are used to achieve tracking, ω_h would always be zero during tracking. It follows:

$$\Omega_1^d = J_1(\Theta)^{-1} *^s V_d \tag{9}$$

where $\Omega_1^d = [\omega_t, \omega_l, \omega_r]^T$ and $J_1(\Theta)$ is 3×3 submatrix of $J(\Theta)$.

3.4.3 Tracking while holding the gaze angle equal to 90°

If we want the gaze angle is 90° during tracking, the motion of left and right vergence joint must satisfy: $\omega_l = -\omega_r$. It follows:

$$\Omega_2^d = J_2(\Theta)^{-1} *^s V_d \tag{10}$$

where $\Omega_2^d = [\omega_h, \omega_t, \omega_l]^T$ and $J_2(\Theta)$ is the 3×3 submatrix computed from $J(\Theta)$.

3.4.4 Tracking with VOR

Suppose that in order to achieve a VOR we want the head to pan with speed ω_h, then the following relationship must hold (J_h is the first column of $J(\Theta)$):

$$\Omega_1^d = J_1(\Theta)^{-1} * ({}^sV_d - \omega_h * J_h) \tag{11}$$

3.5 Visual Correction

For saccade, if the position of the object of interest is known inexactly, the visual correction and VOR can be combined as ($K_{p/v}$:gain matrix):

$$\Omega_1 = J_1^{-1} * (K_p * ({}^sX -{}^s X_a) + K_v * ({}^sV -{}^s V_a) - \omega_h * J_h) \tag{12}$$

References

[1] F. Du, M. Brady, D. Murray. Gaze control for a two-eyed robot head. In *Proceeding of British Machine Vision Conference 91*, Glasgow, Sep. 1991.

[2] Fenglei Du. The Fundamentals for a two-eyed active vision system. First Year Report, Robot Research Group, Oxford University, 1991.