A MULTI-RATE CONTROL SCHEME FOR A ROBOTIC EYE/HEAD SYSTEM INTEGRATING VISUAL AND SELF-MOTION CUES

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ABSTRACT

In primates, the vestibulo-ocular reflex (VOR) is known to stabilize gaze during head perturbations. Also, the internal brain circuits controlling eye movements are found to operate with neural delays much smaller than delays in visual processing pathways (~2ms vs 150 ms). Based on these biological findings, we present a unified multi-rate biomimetic gaze controller integrating VOR mechanisms (self-motion cues) with tracking (pursuit and saccades) for a robotic head with two cameras. The controller uses automatic parametric switching in shared premotor circuits to alternate between two movement types: smooth pursuit (slow phase) relying on visual feedback, and fast blind corrective jumps (fast phase) producing nystagmus. During fixation or tracking of a target (slow phase), a head-motion sensor (VOR) detects head rotation direction and drives the cameras in the opposite direction so that gaze in space remains on the visual target. A multi-rate control scheme is used to overcome inherent delays in the visual system limited to a 30Hz frame rate. Adding prediction and memory (PDI controller) in the visual feedback copes better with visual delays and allows slow tracking bandwidths near 2Hz. The rest of the controller operates at 600Hz: since the saccade circuit is effectively blind, the higher rate controller operation allows increasing saccade bandwidths without ringing to over 30Hz. In this paper, we describe the controller model and we present simulation results to demonstrate its performance.

INTRODUCTION

The mammalian gaze control system uses a dual-mode scheme: premotor circuits switch to a fast (saccadic) mode to re-capture a fleeing target, then switch back to the slower (pursuit) mode to continue stable tracking. Simultaneously, to cope with head perturbations, primates possess a vestibular system located in the inner ear that measures angular and translational head acceleration, to cope with head perturbations. This system forms the VOR whose function is to stabilize gaze direction in space despite perturbations. In the literature, many eye/head robotic controllers built to mimic biological tracking followed a parallel architecture where selected branches or controllers are designed to control a specific aspect of eye/head motion [1, 2, 3]. The effectiveness of such architecture is challenged by the difficulty to achieve smooth coordination between the independent branch outputs as stated by Coombs and Brown [1]. Also these approaches are not really biologically relevant when trajectory planning is employed (as pointed out by Shibata et al [3]).

Our eye/head controller is based on a physiological bilateral model presented by Galiana and Outerbridge [4]. The controller architecture coordinates eye and active head motions, and handles slow phase and fast phase modalities all in the same neural circuitry. There are no separate dedicated controllers. The model was implemented on a robotic vision platform as the first biomimetic design using a unified pursuit/saccade network and internal parametric switching so a shared premotor circuit can alternate between slow and fast modalities [5, 6]. Later, Lee and Galiana incorporated additional physiological clues of prediction and memory (PDI controller) to refine the controller performance for pure visual tracking [7].

In this paper, we extend the model by adding a VOR mechanism to reject head perturbations and by using a multi-rate control scheme to improve fast phase response and bandwidth. Simulation results are presented incorporating the robot hardware dynamics.

METHODS & MODEL DESCRIPTION

Symmetry in our bilateral controller mimics the known coupling between left and right brainstem networks [4]. Movements of the two cameras are coupled to insure fused binocular images. Reciprocal pathways between the two sides generate common and difference modes that support disconjugate tasks [4, 8]. The bilateral controller we present provides conjugate and vergence pursuit, saccade, and VOR mechanisms by using one controller that imitates biology. Figure 1 describes the one-dimensional bilateral controller in its equivalent dynamic forms [7] when using slow phases (pursuit, VOR) or fast phases (saccadic) modes for horizontal movements of ‘eyes’

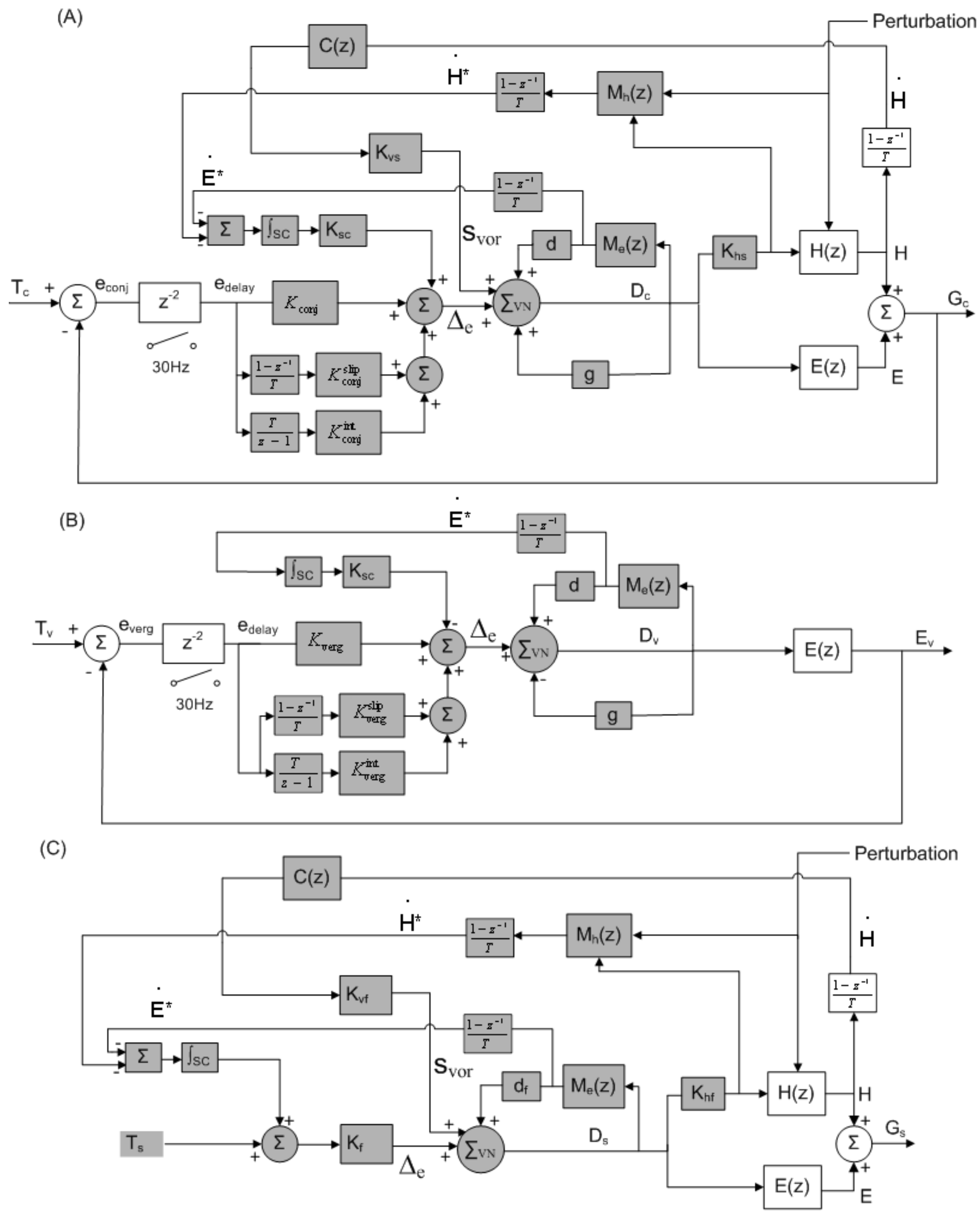

Figure 1: Gray components indicate internal controller elements; white components indicate sensory sources (controller inputs) or system plants. $M_e(z)$ and $M_h(z)$ are internal models of eye ($E(z)$, a first-order low-pass system) and head ($H(z)$, a second-order low-pass system) plants, $C(z)$ is the semicircular canals high-pass filter, g is the reciprocal inhibitory gain in the original bilateral system, and (d/df) are the feedback inner loop gains. Gaze position is the sum of eye and head positions (G=E+H). (A) 1-D PDI conjugate controller. The delayed retinal error (e_{delay}) is processed to generate scaled position, slip and integrated error with appropriate weights ($K_{conj}, K_{conj}^{slip}, K_{conj}^{int}$). This combined sensory signal is compared to a weighted (K_{sc}) integrated sum of internal estimates of eye velocity ($\dot{E}^*$) and head velocity ($\dot{H}^*$) to produce a motor error (Δ_e). Actual head velocity generates a filtered ($C(z)$) and weighted (K_{vs}/K_{vf}) sensory signal (S_{vor}) to provide VOR functionality. Both Δ_e and S_{vor} signals are combined at the summing junction ($\sum_{VN}$) to provide plant drives. (B) 1-D PDI vergence pursuit controller – no head. (C) Fast phase (saccadic) controller: The reciprocal inhibitory links break apart (g=0) and the visual feedback is removed. Saccades are performed individually for each eye and can be disconjugate. The initial target T_s is computed from internal eye and head states and initial retinal error at saccade-startup.

and head. Depending on the parameter set, the same bilateral circuit will i) coordinate vergence and version in the binocular system for stable tracking even in the presence of head perturbations (Figure 1A and B), or ii) provide rapid correction of tracking errors (fast phases, Figure 1C) for each camera. The slow phase operates within a visual feedback loop: the version (conjugate) controller includes both cameras and the head trajectories, but the vergence controller is independent of the head since it does not modify the angle between both eyes. Conjugate and vergence errors (e_{conj} and e_{verg} in Figure 1) are linear combinations of left and right retinal errors as explained in [6]. If the delayed retinal error (e_{delay} in Figure 1) exceeds a threshold during slow phases, the controller switches automatically to fast phase mode which does not use visual feedback. The error between gaze and a fixed internally computed target (T_s in Figure 1) is quickly reduced with a new parameter set in the controller before switching back to slow phase mode. Several studies [9] support the existence of such circuit sharing and neural switching during biological target tracking. In Figure 1A, the motor error Δ_e is computed based on combining position, slip and integrated retinal error (e_{conj}/e_{verg}, PDI controller) and comparing it to the sum of integrated estimates of eye velocity $(\dot{E}^*)$ and head velocity $(\dot{H}^*)$. This replicates known visual slip signals in the brainstem and spatial-temporal integration of target locations in the map of the superior colliculus (SC) [10]. The summation junction ($\sum_{VN}$ in Figure 1) fuses sensory signals from input and motor drives from the output of the controller. Its function resembles the physiological function of the vestibular nuclei. The VOR signal (S_{vor} in Figure 1) is generated by the feedback path composed of head plant H(z), sensor filter C(z) through a weight (K_{vs} or K_{vf}) at the summation junction ($\sum_{VN}$). During slow phases, K_{vs} is negative to provide normal VOR functionality (eye velocity opposite to head velocity). During fast phases, K_{vf} has a small value so as not to hinder gaze speed.

Simulations have been carried out using MATLAB Simulink, based on the robot hardware models identified in [6]. The visual delay component (z^{-2} in Figure 1) runs at 30Hz, the rest of controller runs at 600Hz (e_{delay} in Figure 1 is updated at the low-frequency sampling-rate and used by the controller at the high-frequency sampling-rate). With this high rate data acquisition, the system can end the fast phase trajectory before it overshoots, a problem in prior versions [6, 7]. Furthermore since fast phases are executed blindly with no visual information, the high internal rate allows large increases in fast phase bandwidth. A problem can be caused by the delay and multi-rate scheme when the system switches back to slow phase: the real error (e_{conj}/e_{verg}) is reduced, but delayed error (e_{dealy}) is still large leading to another fast phase and overshooting. As a simple solution, the fast phase end error is retained at the start of the next slow phase (reset) until a meaningful update happens in e_{delay}. An alternative would be model-based extrapolation and prediction using the derivative and integral states of e_{delay} to optimize prediction at the high-frequency sampling-rate.

RESULTS

In all figures, black horizontal bars in the graphs indicate a fast phase segment. Figure 2 shows a large

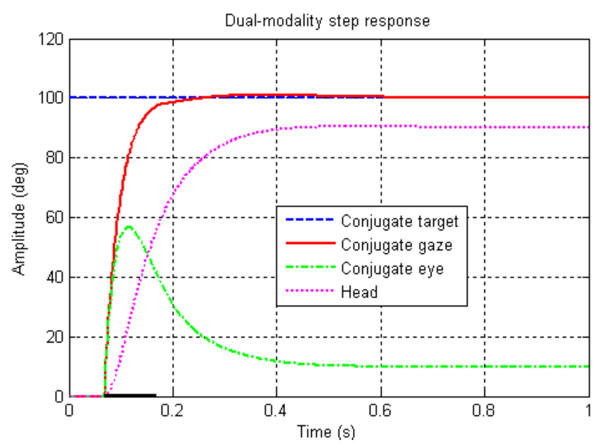

Figure 2: Gaze shift with switching for a step target of 100°. Gaze=Eye+Head.

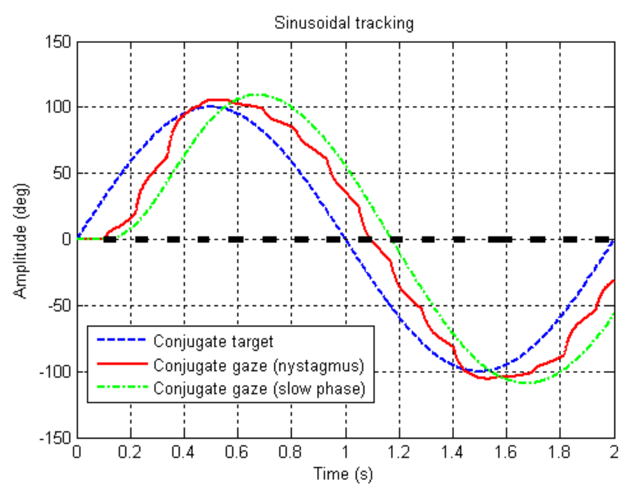

Figure 3: Sinusoidal pursuit of a 0.5Hz, 100° target. The short-dashed line shows the controller's response when fast phase is disabled.

gaze shift using dual-modality control, the effect of visual delay can be seen in the delayed response. Bandwidths of slow and fast phases are 2Hz and

5.5Hz, respectively. Figure 3 shows the controller tracking performance for a large amplitude sinusoidal target. The nystagmus (sequence of slow and fast phases) response has smaller tracking errors compared to a pure slow phase response.

Figure 4 illustrates how visual and self-motion cues cooperate in a gaze shift while rejecting head perturbations beyond the controller's visual bandwidth. Figure 5 demonstrates the controller performance with a ramp target while rejecting head perturbations. Due to PID control, only one fast phase is needed, and then the controller settles into slow phase very quickly and maintains a small tracking error.

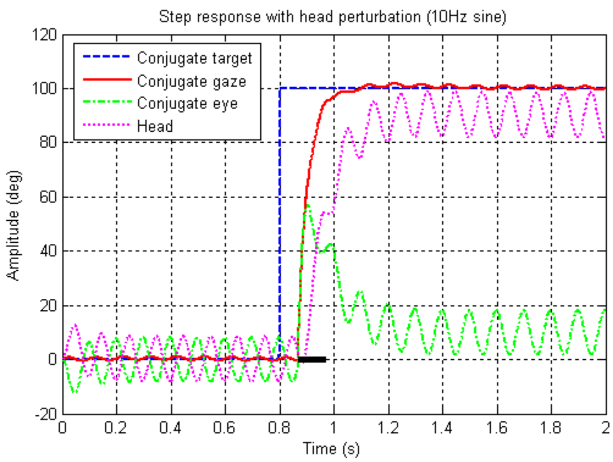

Figure 4: Response to a step target of 100° in the presence of a 10Hz sinusoidal head perturbation starting at t=0.

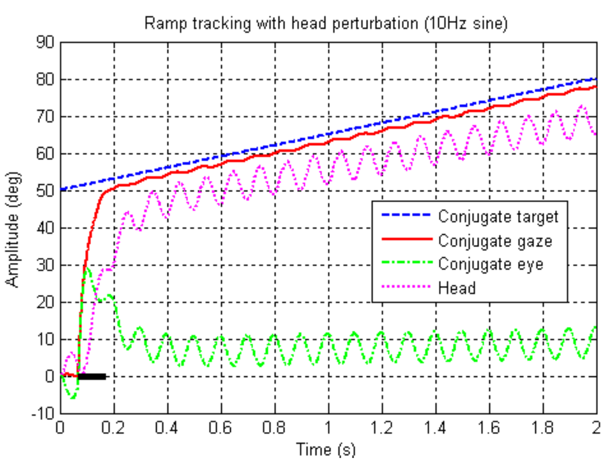

Figure 5: Response to a medium speed (15°/s) ramp target starting at 50° in the presence of a 10Hz sinusoidal head perturbation starting at t=0.

CONCLUSION

The 1D bilateral controller presented here allows simultaneous fusion of visual and self-motion sensory information, stable slow/fast phase switching and eye/head control in an integrated manner for the purpose of target tracking and head perturbation rejection. A multi-rate control scheme was used to prevent fast phase responses from overshooting and to increase its bandwidth. A model-based input extrapolation solution is being implemented to improve the multi-rate controller performance at the points of mode switching. Simulation results demonstrate the controller's ability to track large amplitude target steps and sinusoidal targets as well as its capacity to reject head perturbations. The controller can be extended to 2D/3D (horizontal, vertical, torsion) eyes/head systems and to the fusion of additional sensory sources by stacking and interconnecting the 1D system. The parameters used here were tuned to allow for the known dynamics of our robotic components in the internal models. The next step is to implement the controller on the available humanoid robotic head using real-time computer control.

ACKNOWLEDGEMENTS

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