Robot Head Stabilization During Periodic Locomotion Using Adaptive Dynamical Systems

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Abstract: We present a gaze stabilization system using only visual information as feedback for a self tuning dynamical system. We describe how the dynamical system tunes its internal parameters to those of the optical flow information to generate compensatory commands. We show that the system can be applied to head stabilization during periodic locomotion, but also to tracking periodically moving objects.

Keywords: gaze stabilization, adaptive frequency oscillators, dynamical systems, optical flow, vision, locomotion.

1. INTRODUCTION

Robot head stabilization is usually achieved by using a fast vestibular sensor in the head of the robot as main sensory input and applying a gain function to the rotational information it provides to generate compensatory commands for the head. These gains are usually modulated by computing the remaining retinal slip in the camera image, typically using optical flow ([5], [2], [3]). These approach reach good performance but require the presence of both a camera and a vestibular sensor in the head of the robot. Furthermore they usually can handle only rotations of the head. Typically, during locomotion, the motion of the head of the robot is a combination of rotations and translations.

In this paper, we investigate how well the head can be stabilized by using visual information alone. This may seem like a big restriction due to the relative slowness of the camera sensors, but since our main target is gaze stabilization during locomotion, we can make some simplifications. Assuming that the motion of the head of the robot during locomotion around each axis to stabilize is periodic and close to a sine wave, we use adaptive dynamical systems to learn the frequency and phase shift of the optical flow and generate compensatory signals with the proper amplitude to reduce the optical flow to a minimum. The commands are generated at a much higher rate than that of the optical flow, and are, at convergence, perfectly phase locked with the visual feedback. The system then becomes mostly feedforward and tries to predict the parameters of the compensatory signals before the feedback arrives. We show that this system can be used during periodic locomotion and for object tracking similarly.

2. THE DYNAMICAL SYSTEM

Our head stabilization simply uses one oscillator per degree of freedom to stabilize, getting feedback from the optical flow and outputting commands for that degree of freedom. Our oscillator is based on Adaptive Frequency Oscillators (AFOs, [1], [4]), dynamical systems generating sine shaped oscillations and capable of tuning their internal frequency to that of an external forcing signal. The equations of our system are given next:

$$\begin{aligned}
\dot{r} &= \gamma(1-r^2)r && (1)\\
\dot{\phi_1} &= \omega - \sin\phi_1 \epsilon F && (2)\\
\dot{\phi_2} &= \omega - \sin\phi_2 \beta F && (3)\\
\dot{\omega} &= -\sin\phi_1 \kappa F && (4)\\
x &= r\cos\phi_2 && (5)\\
\dot{\alpha} &= -\eta x F && (6)\\
\theta &= \alpha x + O && (7)
\end{aligned}$$

where r is the radius of the limit cycle of the oscillator (i.e. the amplitude of its oscillations), ϕ its phase, ω its frequency and θ its output here used to control the position of the head actuator. α here directly defines the amplitude of the oscillations and O their offset. F is an external forcing signal (here the opposite of the mean optical flow). κ, β, ϵ and η are scaling factors for the forcing signal. This oscillator is equivalent to a standard AFO merged with a Hopf oscillator and sharing its radius and frequency (Equations 1, 2 and 4 define an AFO while Equations 1 and 3 define a Hopf). This oscillator allows us to control the speed of convergence of the frequency, the amplitude and the phase locking of the output oscillations with the forcing signal independently, by setting the corresponding scaling factors.

The amplitude α is initially set to zero. When the oscillator is synchronized with the forcing signal, the correlation between x and F becomes positive on average and the amplitude of the compensatory oscillations α starts increasing. This leads to the optical flow decreasing until it reaches a minimum, causing frequency, amplitude and phase shift to stop evolving. Perturbations in the parameters of the forcing signal are tracked and damped out by the system.

3. THE VISUAL FEEDBACK

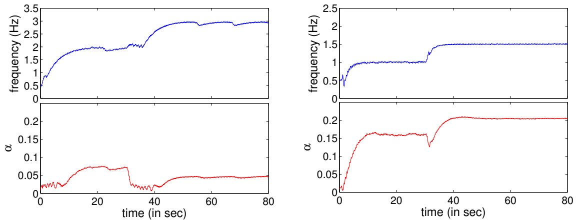
The oscillator described before generates sine shaped oscillations but outputs nothing in open loop since the amplitude α is initially set to 0. To bring the system to generate compensatory signals, it has to be excited by a properly chosen signal. It is necessary and sufficient that the chosen feedback satisfies the following conditions: it should have zero mean, have the same frequency and phase as the motion of the head of the robot and decrease monotonically to zero when the head is stabilized around the considered axis. Note that the signal can come from any sensor and does not need to be an estimate of the head rotation. In this paper we use optical flow since it does not require any extra sensor, is very easy to compute and by default satisfies the conditions given earlier.

To stabilize the gaze of the robot using three axis in the head we typically use three instances of our oscillator with as forcing signals F the y component of the mean optical flow vector for the pitch axis, its x component for the yaw, and for the roll the y component of the difference between the mean vectors computed in the left and right quarter of the camera image. Note that the forcing for the roll axis assumes that the actuator rotates the camera around the center of the image, which is not always true. In particular, for robots having two eyes distributed around the actuator axis, this forcing may be adapted using the left quarter of the left image and the right quarter of the right one.

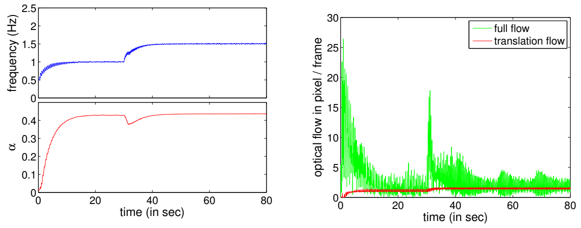
4. RESULTS

We applied our system in simulation on the Hoap2 humanoid robot walking and the salamander shaped robot *Salamandra Robotica* swimming, with qualitatively similar results (check the video[1]) Figure 1 shows the evolution of the important quantities of the system when the salamander robot is swimming. *Salamandra Robotica* is a modular 12 DoF robot controlled by Central Pattern Generators (CPG) allowing it to swim by generating a traveling wave along its body. For our experiment, the frequency of the swimming wave is initially set to 1Hz and switched to 1.5Hz at $t = 30s$. The frequency converges to that of the forcing signal for each axis. Note that the frequency of the motion around the pitch axis is twice that of the other axis. This is specific to this gait and environment and is discovered automatically by the system. When the change of frequency occurs at $t = 30s$, the system tracks it and converges to the new values. The compensatory commands generated cause the optical flow to be reduced to less than 5 pixels/frame, almost half of which is due to the forward motion of the robot.

As said earlier, we use only visual information, optical flow, to stabilize the head of the robot. In addition to the aforementioned pros of doing that, using visual feedback has the advantage of giving movement information independently whether the robot is moving or an external object is moving in front of the robot. Thus the system can be applied without any modification (except for rescaling of the flow amplitude) to object tracking. When using optical flow, this assumes that only the object provides optical flow information (i.e. the rest of the scene is uniform). Instead, simple blob detection or object segmentation may be used. We successfully applied the system on the real Hoap3 robot tracking an apple attached to a spring allowing it to oscillate in front of the robot with different frequencies for the vertical and horizontal axis.



(a) pitch axis (b) roll axis



(c) yaw axis (d) optical flow

Fig. 1: Evolution of the frequency and the amplitude (α) of the oscillator when the salamander robot swimming. The frequency of swimming is initially 1Hz and at t = 30s the frequency is switched to 1.5Hz. Figure 1d shows the evolution of the mean optical flow magnitude over time as well as the flow due to the forward motion of the robot

5. CONCLUSION

We presented a method for stabilizing the gaze of the robot using an adaptive dynamical system excited by the optical flow information from the camera image. We showed that the system can be applied for periodic locomotion or for tracking periodically moving objects. At the moment, the main limitation of the system is the assumption of a nearly sine shaped motion of the head. In cases where the head motion is not sine like, the performance of the decreases. Future work will include ways to overcome this limitation, notably by embedding adaptive shape filters in the current dynamical system.

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