Journal of Mechanical Science and Technology 21 (2007) 930~934

Journal of
Mechanical
Science and
Technology

Biomimetic Control for Adaptive Camera Stabilization in Driver-Assistance Systems

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(Manuscript Received November 16, 2006; Revised January 8, 2007)

Abstract

Throughout the last decade, a large number of electronic driver-assistance systems have been developed in order to improve vehicles' comfort and safety. Up to now, they more or less all rely on odometric data. However in the future, a new form of information is likely to be used: visual sensors, e.g. cameras, can provide additional knowledge on traffic and the vicinity. This paper presents an inertially stabilized camera platform for high precision tracking of points of interest, that has been developed within the project FORBIAS (Research cooperation for biomimetic assistance systems). The inertial stabilization is based on a specially designed sensor system that uses MEMS components in connection with a biologically inspired control algorithm for adaptive enhancement and online calibration of the gaze stabilization system.

Keywords: Driver assistance system; Adaptive control; Biomimetic camera stabilization; Inertial measurement unit

1. Introduction

A new form of driver assistance systems recently became available for drivers of highclass cars: both DaimlerChrysler and BMW have introduced driver assistance systems based on infrared cameras. BMW's night vision uses a car-fixed wide-angle camera in the rearview mirror to detect obstacles. The next step will be a pivotable camera system with telephoto lens. Due to the small aperture angle of less than 10°, these systems need to be actively stabilized. Since latencies of the image processing path amount to up to 70 ms, only inertial stabilization with inertial measurement units (IMU) is fast enough to ensure stable images. With fiber optic gyroscopes being far too large and expensive, cheap but inaccurate MEMS sensors have to be used. The task is similar to that solved by the vestibulo-ocular reflex in biological systems from the earliest vertebrates to humans. The vestibular organ in the inner ear measures the motion of the head in space. Its signals are transmitted along a direct pathway to the extra-ocular eye muscles to stabilize gaze. In order to calibrate the system and cope with changes, for example, due to ageing, a second adaptive path distributes vestibular signals but also efference copies of muscle commands onto so-called parallel fibers in the cerebellar cortex. Purkinje cells form adaptive synapses with the parallel fibers, and their output is transmitted to the eye muscles. The adaptive process itself is driven by climbing fibers containing visual information on stabilization errors and acting on a one-to-one basis on the Purkinje cells. We use the same principle of adaptive multi-sensor fusion to continuously calibrate MEMS sensors of an IMU for camera stabilization in a driver-assistance system. Residual optic flow of the stabilized camera is calculated online and projected onto the sensitive

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nominal axes of the IMU. For each nominal axis, all sensors are adaptively combined, thus compensating for nonorthogonalities in the assembly. This allows loose tolerances for manufacturing and reduces production costs. In first road trials together with a German car manufacturer, the system eliminated nearly all correlation between optic flow and gyro signals, which means excellent stabilization of the camera platform.

2. The inertially stabilized camera platform

The system for camera stabilization consists of three main parts: a 6 degree-of-freedom (dof) inertial measurement unit (IMU) detects the vehicle's rotations and accelerations. The vehicle motion is then compensated for with a 2 dof camera motion device. Due to low amplitudes, rolling of the car is neglected. The whole system is controlled by a biologically inspired adaptive algorithm which evaluates sensor signals and calculates the required actuator angles in real time. In this section, the sensory system and control algorithms are presented in detail. For further information on the camera/gaze manipulation device please refer to the accompanying paper by Wagner et al.

2.1 A miniaturized inertial measurement unit

In a future application of the inertial measurement unit in connection with gaze stabilization, its position will most probably be inside the rearview mirror. Commercially available IMUs with a design envelope of at least 50×38×25mm³ are far too big for this purpose. Therefore a highly miniaturized IMU had to be designed within the FORBIAS project. The sensors' measurement range was defined by the industrial partner BMW. Angular rates of up to 1 rad/s and accelerations up to 2g have to be resolved. Although most vehicle motion is in the sub-10Hz range, the IMU's bandwith should exceed 80Hz to be sufficient for wide variety of different applications.

Analog Devices' ADXRS series is currently the best choice for low-cost measurement of angular rates. Due to pin compatibility, both sensors with measurement ranges of 150 and 300 deg/s can be populated according to the needs of the application without changes in the printed circuit board (PCB) layout. The low noise of $0.05\deg/s/\sqrt{Hz}$ and $0.1\deg/s/\sqrt{Hz}$ Hz respectively leads to a good angular rate resolution. The analog sensor signals are converted by a MAX1226 Analog-Digital-Converter (ADC), further reducing noise with up to 32x oversampling (@1kHz).

Accelerations are measured by the recently commercialized LIS3LV02DQ sensor provided by STMicroelectronics. The main advantage of this accelerometer is its compact packaging of three sensitive axes on one single QFN28 (7×7×1.8 mm) chip. Additionally, the sensor has a digital SPI interface that does not require further ADC channels. With a resolution of better than 1mg, it sufficiently fulfills the requirements.

The whole IMU is controlled by an Atmel AT90 CAN128 microcontroller that guarantees sufficient internal SPI bandwidth by an external oscillator. It provides an onboard CAN controller that is used in cases when a high frame rate is required due to possible data rates of up to 1Mbit/s. In addition, the IMU can be connected to regular PCs with its RS232 interface.

The main challenge for the miniaturization is the necessary orthogonality of the sensitive axes. With the gyroscopes being sensitive in their out-of-plane direction, at least three orthogonal PCBs are required. This task is solved by the special design of the circuit boards. For the mCube (Fig. 1), so-called Wirelaid PCBs are used which feature small wires with a diameter of 150 mm inside the boards. After popula-

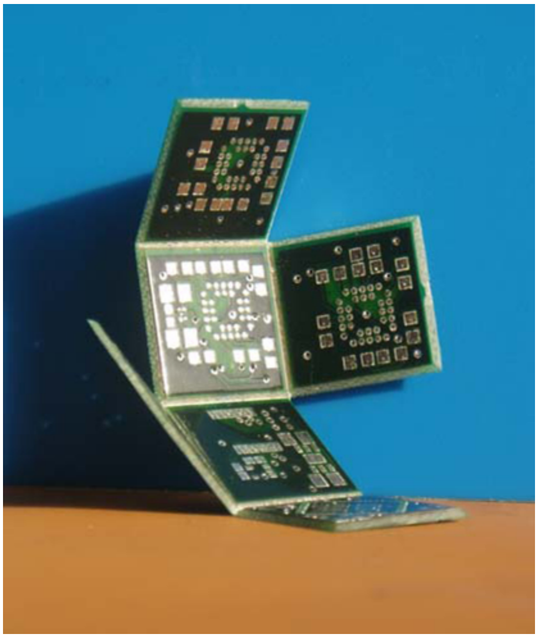

Fig. 1. First prototype of the highly miniaturized inertial measurement unit mCube, unpopulated and half folded.

tion, small notches are milled into the board that allow folding. In comparison to stiff-flex PCBs, the used technology leads to a stiffer setup of the cube and overall dimensions of only 15×15×16mm^3.

2.2 *Biologically inspired control algorithms*

One of the goals of the project FORBIAS is the development of biomimetic algorithms for the online enhancement of the inertial measurement unit and adaptive calibration of the gaze stabilization system (Guenthner et al., 2005). In human beings, gaze stabilization is achieved by the so-called vestibulo-ocular reflex. Head rotation is measured by the semi-circular canals in the inner ear, this information is then used as stabilization command. In a direct pathway, the raw signals are sent to the extra-ocular eye muscles assuming time-invariant characteristics. Due to involving only three neurons, this stabilization has a very low latency of only 7ms. For the engineering application, the relationship can be expressed as

$$b = JS\omega \tag{1}$$

with b being the output of the brainstem, angular rates as measured by the sensory system ω, the diagonal matrix S of nominal sensor sensitivities and the Jacobian J projecting angular rates onto the axes of the camera motion device. This pathway has a low latency, however it is not adaptive and does not account for temporal changes for example due to aging (of the biological system) or changing temperatures (in the technical system). In addition, it is not calibrated and has no accurate knowledge on sensitivities. Therefore a second adaptive pathway is superimposed (Fig. 2). Vestibular signals and some possible variations are transmitted to so-called parallel fibers in the cerebellar cortex (Lisberger, 1998; Dean et al., 2002). In the technical system as variation only the signals' derivatives are currently used

$$q = \begin{pmatrix} \omega \\ \dot{\omega} \end{pmatrix} \tag{2}$$

The output of the cerebellar cortex are Purkinje cells which form adaptive synapses with several thousand parallel fibers q but have only one output signal. The adaptation of the weight matrix for the three dimensional case

$$W = \begin{pmatrix} w_p & w_d \end{pmatrix}, \qquad w_p,\, w_d \in \Re^{3x3} \tag{3}$$

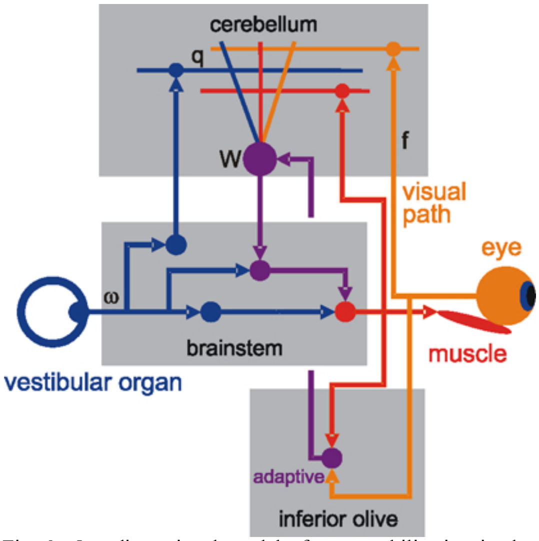

Fig. 2. One-dimensional model of gaze stabilization in the biological system.

is driven by one climbing fiber per Purkinje cell inhibiting an error signal, for example optic flow

$$f = \begin{pmatrix} f_x \\ f_y \\ f_z \end{pmatrix} \tag{4}$$

projected onto nominal sensor axes. The high latency of the image processing in the visual cortex only affects the time of adaptation but does not induce delays in the gaze stabilization. The weight update itself can be modeled with an anti-Hebbian learning rule and learning rates β_p and β_d for the proportional and derivative signals respectively:

$$\dot{w} = -fq^T\beta = \begin{pmatrix} f_x \\ f_y \\ f_z \end{pmatrix} \begin{pmatrix} \omega_x & \omega_y & \omega_z & \dot{\omega}_x & \dot{\omega}_y & \dot{\omega}_z \end{pmatrix} \begin{pmatrix} \beta_p E^{3x3} & 0^{3x3} \\ 0^{3x3} & \beta_d E^{3x3} \end{pmatrix} \tag{5}$$

The output of the adaptive path

$$p = J\begin{pmatrix} w_p & w_d \end{pmatrix} \begin{pmatrix} E^{3x3} & 0^{3x3} \\ 0^{3x3} & 0^{3x3} \end{pmatrix} pf, \quad d = J\begin{pmatrix} w_p & w_d \end{pmatrix} \begin{pmatrix} 0^{3x3} & 0^{3x3} \\ E^{3x3} & 0^{3x3} \end{pmatrix} pf \tag{6}$$

for the proportional part p and the derivative part d are then added to the brainstem output b

$$e = d + \int (b + p)dt \tag{7}$$

to form the inverse gaze stabilization command e. In order to avoid drift, a leakage factor can be introduced

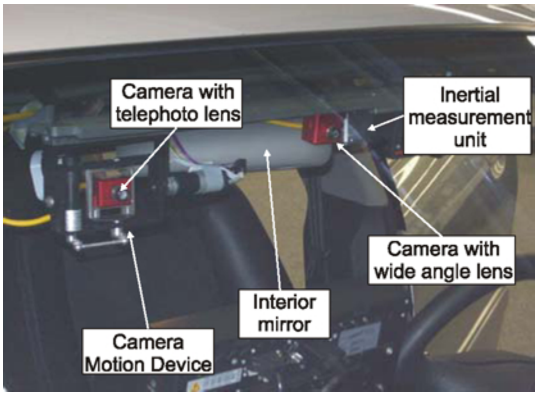

Fig. 3. Camera motion device and inertial measurement unit mounted in a test vehicle. The rigidly mounted camera gives an overview of the environment and detects points of interest for the pivotable camera with telephoto lens.

in Eq. (7). Details on the camera motion device and its local actuator control can be found in the MOVIC companion paper by (Wagner et al., 2006).

3. Experimental evaluation in test drives

For the experimental evaluation of the complete gaze stabilization system a test vehicles supplied by the FORBIAS industrial partner Audi has been equipped (Fig. 3). A wide angle camera is used for getting a general overview of the environment and to detect the primary point of interest. That target is then focused by the pivotable and stabilized camera with telephoto lens. In order to avoid interdependencies, adaptation was switched off while target pursuit was in operation.

Test drives took place on German motorways at car velocities of about 130-140 km/h. Three different modes were tested: in a first mode a line marker about 60m ahead was detected and then followed by the pivotable camera until it reached a minimal distance of 20m in front of the car. Then the next marker was chosen. In a second mode, the line dividers 40m ahead were chosen as target. The third series of tests did not focus on a specific target but stabilized the camera around its neutral position. In order to avoid frequent and disturbing gaze shifts, stabilization was performed on a velocity basis and saccades were only initiated when the actual line of sight differed by more than 1.5 deg from the reference given by image processing.

Figure 4 (right) shows measured data during a test drive in the second mode. As a reference, in the left column pitch rates and the corresponding optic flow

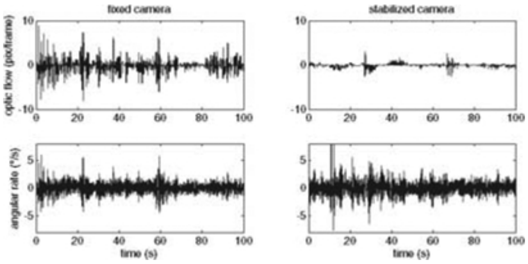

Fig. 4. Optic flow and angular rates (pitch) during test drives with target fixation 40m ahead for the stabilized camera (right) and a reference drive with actuators switched off (left).

(OF) are plotted for a test drive with the actuators of the camera motion device switched off. Both scenarios show comparable angular rates of up to 5 deg/s which sets high demands for angular resolution and accuracy. In the unstabilized case (left) optic flow is significantly higher than during the test with biomimetic gaze stabilization. But most important is the fact that in the right column the correlation of residual optic flow and angular rates is removed. This means that there is no dependency between the two, thus the OF is not a result of vehicle rotation but of its locomotion and especially overtaking cars.

Conclusions

In this paper an inertially stabilized camera platform for the use with driver assistance systems is presented. A specially designed inertial measurement unit detects the vehicle's rotation and actively stabilizes a pivotable camera with telephoto lens. In order to cope with unknown sensor sensitivities and non-orthogonalities in the sensor mounting, an adaptive biomimetic control algorithm was implemented. The system was evaluated in test drives on motorways at vehicle velocities of up to 130-140 km/h. Camera stabilization removed nearly all detectable correlation of vehicle rotation and image motion thus meaning that the camera was close to perfectly stabilized.

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