Compact High Dynamic 3 DoF Camera Orientation System: Development and Control

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Abstract
This paper reports on the development and control of a compact, high dynamic camera orientation system with three degrees–of–freedom (DoF). The system orients a small camera around its pan, tilt, and roll axes, using a parallel kinematics driven by ultrasonic piezo–actuators. To fit its application as part of a gaze–driven head–mounted camera system (EyeSeeCam) or as an artificial eye for humanoid robots, the camera orientation device was designed to be small in weight and size as well as to replicate the high dynamic movements of the human eye. The mechanical setup is described and the closed loop control architecture, including a dead zone compensation for the actuators, is introduced. Control experiments conducted with the prototype demonstrated that the system performance is comparable to and even exceeds that of the human oculomotor system.

Key words: High Dynamic, Camera Orientation, Parallel Kinematics, Piezo–Actuators, Robot Eye.

1. Introduction

We have developed a portable system that is able to acquire stabilized images, even under dynamic conditions like locomotion, see(1). This so–called gaze–driven head–mounted camera system (EyeSeeCam) is able to track human eye movements and to reproduce them with a camera orientation device with two degrees–of–freedom (DoF). Since the latencies between human eye and camera movements are short (10 ms), the camera orientation device is stabilized only by the human vestibulo–ocular and optokinetic reflexes. Such a system has been used in research of vision in natural environments(2) and for subjective documentation of surgery(3).

To extend the EyeSeeCam to three DoF a camera orientation device that reproduces all rotational DoF of the human eye with a workspace of about ±20 deg to ±30 deg is required. Due to the application the camera orientation device must be designed to follow the movements of a human eye. Thus the system must deal with high velocities of up to 500 deg/s and with accelerations of up to 25000 deg/s². The device must also guarantee short latencies between user eye and camera movements of about 12 ms(4), (5). For wearability purposes, a compact and light–weight design is important.

The literature refers to many camera orientation systems that provide the desired high dynamic orientation changes, but they do not fulfill the requirements for compactness and weight(6)–(8). Smaller devices are often not able to provide, at the same time, the required high velocities and the three DoF(9)–(11). The compact spherical ultrasonic motor depicted in(12) is able to orient a small camera around three axes with high velocities. However, the de-
vice provides only low orientation accuracy. The camera orientation system\(^{(13)}\) that was used for the gaze–controlled camera EyeSeeCam\(^{(1)}\) provided only two DoF. Earlier approaches to implement small–sized camera orientation devices\(^{(14)},(15)\) utilized model aircraft servo actuators to drive the system. These actuators only have a unidirectional PWM interface. Therefore, by default an additional dead time of 20 ms is introduced. Since the interface is only unidirectional, it is not possible to readout the actual actuator position. Thus, no overlaid closed loop control structure can be implemented. The backlash of the built–in gear box constitutes a further drawback of the drive system.

Since no known system was able to fulfill the requirements, a new system was developed. The mechanical design of the device is presented in Section 2, where also the accessible workspace and the quantization error are reported. In Section 3 we focus on the piezo–actuator nonlinearities and we propose methods to deal with them. Beside the selected closed loop control architecture, experimental control results are introduced in Section 4. Section 5 recapitulates the paper and highlights future plans.

2. Mechanical design

To suit the proposed application, as part of a gaze–driven head–mounted camera orientation system or as an artificial eye for humanoid robots, a compact and light–weight design is important. Thus, the developed camera orientation device is based on a parallel kinematic system, with three rotational DoF. The use of a parallel kinematics has the advantage that all mounted actuators are stationary. Therefore, only minor inertial masses must be oriented as opposed to a serial kinematics, which makes it feasible to use small and light–weight ultrasonic piezo–actuators (Physik Instrumente, P–661). For this reason the size and the weight of the camera orientation system are kept small. The cost is a more complex mechanism compared to a serial kinematics\(^{(16)}\). Note that the introduced kinematic design is inspired by a parallel robot that was previously suggested by Merlet, see\(^{(17)}\). However, the size and the weight of the system presented here are reduced. Moreover completely different actuator as well as sensor concepts are used to cope with the desired high dynamic movements.

The selected kinematic scheme is depicted in Fig. 1 and a prototype of the developed camera orientation system is shown in Fig. 2. Using this device a small camera can be oriented around its vertical (pan), horizontal (tilt), and longitudinal (roll) axes.

![Fig. 1 Kinematic scheme.](image)

As mentioned before, the three mounted linear piezo–actuators are stationary. Prismatic joints \(P\) and push rods (4, 5, and 6) are used to transmit the actuator movements to the orientable camera platform 7. The push rods are equipped with small spherical joints \(S\) on both sides. Thus, so–called PSS (prismatic, spherical, spherical) chains are formed. The chosen small spherical joints guarantee a high accuracy along their vertical and diagonal axes. To avoid backlash around the longitudinal axis the joints are preloaded with three tension springs that mutually connect the push rods. For a better overview the tension springs are omitted in Fig. 1. An additional passive chain with a spherical joint \(S_M\) (Kullborg Eng.) is used to
connect the camera frame and the actuator base plate. This main spherical joint ensures the required three rotational DoF. On both sides (actuator base and camera frame) the pivot points of the push rod spherical joints are arranged in a circle, with 120 deg off set between each other. To avoid singularities over the entire required workspace, the actuator base plate and the camera frame are rotated 60 deg with respect to each other in the kinematics home position. To minimize the driven mass, the orientation of the camera platform is not measured directly, but is calculated from the actual positions of the linear actuators. For this purpose, incremental encoder stripes are attached to the prismatic joints. These stripes are evaluated by magnetic encoder modules and by reference sensors, both of which are mounted on the actuator base plate. To calculate the actual camera orientation from measured actuator positions, the inverse kinematic solution of the presented camera orientation system is deduced. The inverse kinematics is further used to calculate and optimize the workspace of the system as well as for the closed loop controller architecture. Since the derivation of the inverse kinematics and the optimization of the workspace/package ratio is extensive, it is presented in an additional paper. Interested readers refer to (18).

The main specifications of the developed camera orientation system are summarized in Table 1.

<table>
<thead>
<tr>
<th>Propriety</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Covered workspace</td>
<td>84 % of a cubic volume with ±30 deg</td>
</tr>
<tr>
<td></td>
<td>100 % of a cubic volume with ±19 deg</td>
</tr>
<tr>
<td>Angular velocities</td>
<td>&gt; 1000 deg/s</td>
</tr>
<tr>
<td>Worst quantization error</td>
<td>0.0169 deg</td>
</tr>
<tr>
<td>Mean quantization error</td>
<td>0.0067 deg</td>
</tr>
<tr>
<td>Overall size*</td>
<td>44 x 44 x 100 mm³</td>
</tr>
<tr>
<td>Push rod length</td>
<td>42.86 mm</td>
</tr>
<tr>
<td>Actuator travel range</td>
<td>± 11 mm</td>
</tr>
<tr>
<td>Overall mass*</td>
<td>100 g</td>
</tr>
<tr>
<td>Mass movable parts*</td>
<td>40 g</td>
</tr>
</tbody>
</table>

* The presented values do not account for cabling.
To cut down on weight most of the custom–made parts are manufactured of aluminium alloy (AlZn5.5MgCu). To guarantee supplementary stiffness the push rods are manufactured of a high alloy CrNi steel (1.4305). The system has a size of 44 x 44 x 100 mm³ and an approximate weight of 100 g (without wiring). Note that the mass of the movable parts without wiring is about 40 g. The camera orientation device covers about 84% of a cubic workspace volume with an edge length of ±30 deg for all three orientations. It is possible to fully cover a cubic workspace volume with an edge length of about ±19 deg for all three orientations. In Fig. 3 the workspace of the developed camera orientation system is presented. Due to the mechanical design and because of the joint limitations the covered workspace is not a cuboid but a twisted sphere.

![Fig. 3 Covered workspace.](image)

To reduce weight and complexity, only the positions of the linear actuators are measured. From these positions the actual camera orientation is calculated. Fig. 4 shows the color–coded worst quantization error of all three orientations over the entire workspace. Due to the nonlinear relation between the actuator positions and the camera orientation the angular resolution is not constant.

![Fig. 4 Worst quantization error over the workspace.](image)

As can be seen from Fig. 4 the worst quantization error of about 0.0169 deg occurs when the pan, tilt, and roll orientations are maximal. Note that normally a human does not keep his eye very long in such an uncomfortable position, see\(^{19}\). To yield a more practical value, the mean quantization error over the entire workspace is calculated to be 0.0067 deg. According to Brunstetter\(^{20}\) the accuracy of human extreme gaze ocular fixation is about 0.166 deg. Thus, it can be confirmed that the developed camera orientation device provides a higher angular resolution than the human oculomotor system.

3. **Dead zone compensation**

To drive the selected piezo–actuators, special power electronics are needed (C–184, *Physik Instrumente*). Preliminary control experiments show that for small input signals to the
power electronics no movements of the piezo–actuators can be registered. This phenomenon, which can be described as a dead zone, has two major reasons. The first is the static friction of the mechanical setup, which must be overcome by the actuators. The second is the adjustment of the power electronics itself. Potentiometers can influence the characteristic response of the actuators, so that movements also occur for small input signals. Because of the high bandwidth of the piezo–actuators an acoustic noise will be generated in this case. Since the developed camera orientation system is intended to be head–mounted, users should be affected as little as possible. Therefore, the dead zone is enlarged artificially.

To deal with the dead zone, two different compensation approaches have been investigated. Velocity and (static) force measurements are performed with the actuators. First, a neuronal network is trained off–line to fit these characteristic curves, yielding suitable initial values. After that, the gained basic data is refined and adapted during measurements to other actuators while training the neuronal network on–line. In this way the validity of the data is improved and the amount of measurements is reduced. The determined relation between the normed power electronics input signals and the forces produced by the actuator is represented in Fig. 5 as a solid line.

The nonlinear behaviour between power electronics input signal and force produced by the actuators is also rudimentarily described in the data sheet of the piezo–actuators. The few data provided by the manufacturer are matched with the following quadratic equation:

\[ F_A = k_F I_S^2 \, sgn(I_S), \tag{1} \]

where \( F_A \) represents the force produced by the actuator, \( k_F \) is the motor constant chosen to be 2.5 N, and \( I_S \) depicts the normed input signal. This relation is represented by the dashed line in Fig. 5.

As can be seen from the figure, the graph obtained with the quadratic equation differs from the real measurements. From the plot it can be further observed that similar results are gained with both descriptions for small input signals. In this area no forces or movements are produced by the actuator.

Evidently, the dead zone must be compensated to achieve adequate control results. For small input signals (in the range of the dead zone) both descriptions are similar. We therefore investigated which inverse functions adequately compensate for these actuator nonlinearities.

The following measurements were performed with a simple closed loop proportional controller in order to compare the two approaches. Note that without an integral part in the controller the system is very susceptible to inaccuracies in the compensation function. To exclude any influence from the parallel kinematics or from the other actuators, the tested actuator was examined in isolation without any connection to the camera orientation system.

As expected, better control results can be achieved with the adapted compensation that is based on the measurements and the neuronal network. The simple quadratic function from the
data sheet was not sufficient. However, considerable acoustic noise is produced by the better compensation. Therefore, the control gains have been manually reduced in such a way that during the measurements with both compensations only a small acoustic noise is produced. In Fig. 6 the control errors for the different compensations are presented for sinusoidal actuator movements with an amplitude of 10 mm and a frequency of 0.5 Hz.

![Control Error Graphs](image)

**Fig. 6** Control error: Adapted compensation (left), quadratic compensation (middle), without compensation (right).

Less noise was produced by reducing the control gain. This, however, led to inferior control results of the adapted compensation compared to the quadratic compensation (see Fig. 6 left and middle). Further measurements with no compensation at all were performed. The noise is reduced only marginally at the cost of an increasing control error, see Fig. 6 (right).

Thus, the quadratic approach offers the best tradeoff between acoustic noise and nonlinear dead zone compensation. To deal with the inaccuracies, an integral part is added to the closed loop controller, which notably improves the control results. Initial subjective examinations revealed that the integral controller part increases the acoustic noise only slightly.

4. Control strategies

An appropriate control strategy must be chosen to align a camera with desired angles. Experiments with the previously developed camera orientation systems with two DoF\(^{(21),(22)}\) showed that it is much simpler to set up independent controllers for each linear axis then a nonlinear coupled controller for two orientation axes. Therefore, a so-called joint space controller was also developed for the new system with three DoF. It is presented in Fig. 7.

The desired camera orientation angles (\(\alpha^*, \beta^*, \text{and} \gamma^*\)) are transformed to set points for the linear actuators (\(\theta_1^*, \theta_2^*, \text{and} \theta_3^*\)) using the inverse kinematic solution of the system, which is described in detail in\(^{(18)}\). The actual positions of the linear actuators are measured with magnetic encoders. The desired values are adjusted with three separate proportional–integral (PI) controllers. After applying the quadratic compensation, which accounts for the nonlinearity of the actuators, the desired forces (\(f_1^*, f_2^*, \text{and} f_3^*\)) are passed to the power electronics. These devices include the power stages that are required to convert the input signals to the respective piezo–actuator control signals. Note that in order to avoid possible overshoot after large movements the PI controllers are equipped with an integral anti–windup. The advantage of the joint space approach is that the single controllers (one per each actuator) can be started up independently of the other. Once the control parameters are adjusted the entire system is started and the parameters are refined.

To ensure high performance during the following behavior stiff control parameters are chosen. However, if a step arises in the desired orientation, the used PI controllers increase the actuators’ input signal to the maximal value. As a matter of fact, the response characteristic and maximal velocity of the used piezo–actuators differ from one actuator to another. So the overall control result is negatively influenced. Therefore and allowing for the requirements of
high dynamic movements, a so-called rate limiter is used to artificially restrict the velocity of the camera orientation. In this way the periods in which the actuators are in saturation are reduced, and the control performance is enhanced. Note further that a simple linear filter is active for every signal, and thus would introduce an undesirable supplementary dead time, while the used rate limiter is active only for high dynamic signal changes.

Different control experiments were performed with this camera orientation system. Since the device should orient a camera to desired angles, the orientation accuracy (workspace) is of more interest than the linear actuator position (joint space). Therefore, the control results are presented in the workspace and the actual actuator positions are transformed to camera orientations with the deduced direct kinematic solution. Thereby, orientations around the camera’s vertical (pan) axis are described by the angle $\alpha$, around its horizontal (tilt) axis by the angle $\beta$ and around its longitudinal (roll) axis by the angle $\gamma$, see Fig. 1. Due to limitations of space only the measurements with the highest control error are depicted.

First, step response measurements are presented. These experiments are used to simulate the fastest movements of the human eye, saccades. Fig. 8 shows the desired (solid line) and the actual (dashed line) angular position of the camera orientation during the application of a step in the tilt direction from -20 deg to 20 deg with the pan and roll orientations set to zero.

As Fig. 8 (middle) illustrates, the new orientation can be reached in about 40 ms, which results in an average angular velocity of about 1000 deg/s, with only a small overshooting of about 1 %. An angular orientation error in the pan axis of less than 0.7 deg and in the roll axis of about 2.1 deg can be observed for the same small time period. These errors occur because of the parallel structure of the kinematic system. Position errors that arise during displacement of at least one of the linear axes always result in angular errors of all orientations. Due to the
kinematic structure, the roll orientation is the most sensitive, and its error is larger than for the pan orientation. As stated before the maximally achievable velocity is artificially limited to 1000 deg/s by the controller. In this way the required angular velocities of 500 deg/s can be provided and the angular error in the non–tilted axes is reduced. Experiments without this limitation show that it is possible to fulfill steps of 40 deg in less than 15 ms in the roll orientation. Thus, it is possible to reach an average velocity of more than 2500 deg/s with this camera orientation system.

For the next experiments sinusoidal movements with an amplitude of 20 deg and a frequency of 0.5 Hz were used to simulate slow orientation changes of the human eye, so–called slow phases. Such movements were simulated around the roll axis; the other two axes were held at zero. The following behavior results are presented in Fig. 9.

Since the roll axis is the most sensitive axis, it gives rise to the highest error. As can be seen from Fig. 9 (right) the maximal roll angle error is about 0.27 deg. The error in the other two axes is much smaller, about 0.03 deg for the pan axis and about 0.06 deg for the tilt axis. Periodical steps can be observed in the angular error signals, especially for the roll orientation. They occur when the sense of rotation of the simulated eye movements changes and consequently the actuators idle. Before the motion restarts, the non–ideal compensated dead zone must be overcome. As can be seen from the figure, the positioning error increases rapidly during these small time periods.

5. Conclusion

This paper reports on the development and control of a compact, high dynamic camera orientation system that was verified through prototype testing. The described device is based on a parallel kinematics with three rotational DoF. Thus it is able to orient a small camera around its pan, tilt, and roll axes. Small, lightweight, and fast ultrasonic piezo–actuators are used to drive the system. In doing so 84 % of a cubic workspace volume with an edge length of ±30 deg for all three directions is covered. To save weight the camera orientation is calculated from measured actuator positions. While the maximal quantization error is less then 0.017 deg, the mean quantization error is about 0.0067 deg. Thus the camera orientation system provides a higher angular resolution than the human oculomotor system. In addition a closed loop control architecture and an actuator dead zone compensation are introduced. Since the camera orientation device is intended to be used as part of a gaze–driven head–mounted camera or an artificial eye for humanoid robots, the device must cope with the high dynamic movements of the human eye. Step response experiments that were conducted with the developed prototype proved that the proposed system is able to orient a camera around three axes with dynamic movements exceeding those of the human eye. Following behavior experiments moreover showed a good tracking performance. Future plans include tests with one isolated device, the integration into a gaze–driven head–mounted camera orientation.
system, tests with the entire system as well as the investigation of more sophisticated control architectures to yield a better decoupling of the single axes.

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