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Machine vision-based sensing for helicopter flight control

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SUMMARY

Machine vision-based sensing enables automatic hover stabilization of helicopters. The evaluation of image data, which is produced by a camera looking straight to the ground, results in a drift free autonomous on-board position measurement system. No additional information about the appearance of the scenery seen by the camera (e.g. landmarks) is needed. The technique being applied is a combination of the 4D-approach with two dimensional template tracking of *a priori* unknown features.

KEYWORDS: Flight control; Helicopter; Machine vision; Hover stabilization.

1. INTRODUCTION

Military aircraft regularly conduct missions that include low-altitude and near-terrain flight. Civilian aircraft operate in this environment during airborne fire fighting, police surveillance, search and rescue, and helicopter emergency medical service applications. Several fixed-wing aircrafts today operate with terrain elevation maps, GPS and forward pointed radars. Similar systems specialized for helicopters and their flight regime are still under development. The highest workload for helicopter pilots occurs during hover and landing tasks. Under extreme adverse environmental conditions these missions are currently not practicable. Thus, the precision hover mode above a ground fixed or moving target was selected for closer investigation. Up to now, hover position hold control systems in helicopters are based on Doppler radar measurements of the ground speed. Therefore, drifts in the position observation have to be accepted. For a relative position hold system, like hovering above a lifeboat, a new sensor without drift is required. Thus, the Institute of Flight Mechanics of DLR *Deutsches Zentrum für Luft- und Raumfahrt* e.V. (i.e. German Aerospace Center) developed a machine vision system, which is able to observe the helicopter flight state during hover and low speed, based on the detection and tracking of significant but arbitrary features. This system is able to track features free of drift and even sticks to a target while this is moving. No pre-defined landmarks are necessary. New features are continuously extracted from the image data; less suited features are identified and excluded from the tracking process. Feature updating is used to cope especially with rotations.

Within a feasibility study a restricted machine vision system, which is capable of locating and tracking a square, was developed and integrated into a fly-by-wire helicopter. Flight tests demonstrated automatic helicopter hover stabilization above the moving square, being mounted on a car (Figure 1).

This lead to the development of a general machine vision system. The approach is as follows: the on-board video camera looks straight to the ground and produces an image of the ground view. The motion of the helicopter results in the movement of patterns in the image. The most significant patterns are identified and used for a two dimensional template tracking. Together with some inertial sensor data the tracking results are used by a state variable filter (4D-approach) to calculate the spatial orientation and movements of the flight vehicle relative to the ground. This approach was funded by the European Community as a research project for high performance computing. It was carried out in a close co-operation with *Eurocopter and*

Fig. 1. Flight tests demonstrate vision controlled flights.

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Universität der Bundeswehr München (i.e. University of the Armed Forces in Munich).

Today, autonomous helicopter projects are quite popular, e.g. research on vision-based state estimation is also being carried out at the *Carnegie Mellon's Robotics Institute*[1] and at the *Universität der Bundeswehr München*.[2,3]

2. FEASIBILITY STUDY

As a proof of the concept, a machine vision-based system, which is capable of locating and tracking a known target, was developed in 1993/94. An existing model following controller for the forward flight condition of helicopters was adapted for the hover and low speed requirements of the flight vehicle.[4] The algorithms for the detection and tracking of the target are based upon a correlation method using ternary masks. These masks contain elements with values of −1, 0, and +1 only. The machine vision system is able to locate the target in any position and orientation.

After testing the sensing and control system with a hardware-in-the-loop simulation, it was integrated into the fly-by-wire helicopter ATTHeS (Advanced Technology Testing Helicopter System). The target, a black square, was mounted on top of a car. When the machine vision sensor had located the target within a defined range, the pilot engaged the position hold. The car-crew was informed by radio to drive a circle with a velocity of about 15 km/h and a radius of about 40 metres. The control system had to fly the helicopter above the target in constant altitude and with constant heading, while the evaluation pilot flew hands-off. The ground track of the car resulted in all combinations of forward, backward and sideward speeds of the helicopter. This was demonstrated under 15 kt wind conditions with gusts up to 30 kt (Figure 1). The system was used to study helicopter control laws for the hover flight state.[5]

3. GENERAL MACHINE VISION SYSTEM

The system design for the general machine vision system is shown in Figure 2. A feature extraction module deals with the search for distinctive features in a video image. A part of the image is analysed for the localisation of feature areas with high grey level discontinuities. Such areas are good candidates for the feature tracking module, which uses a fast two dimensional template matching algorithm for the tracking of features. The expected position of such a feature is used to reduce the matching process to an image window. The actual position of each feature is fed into a state variables observer, called a 4D-approach,[2] which delivers a state estimation for the helicopter movements. Inertial sensor data supports this task. The predicted orientation of the helicopter in the next time step leads (with some view transformations) to the expected position of each feature in the next video image. This loop is calculated for several features during each evaluation. By comparing expected and tracked position for each feature, its quality is determined and it might be rejected for the next step. New features can be added from the extraction process.

The machine vision system consists of processors which are connected via links (bi-directional communication channels) and via a dedicated video bus (Figure 3). The links are used for the distribution of commands and results; the video bus is used to broadcast the image data. Most processors are a combination of a transputer (T8) and a 100 MHz PowerPc (PPC) processor. A dedicated correlator subsystem is used for the matching of feature templates with image windows. The combined transputer-PowerPC modules, as well as the video bus, were developed by the German company *Parsytec*.[6] The correlator subsystem is an in-house development of DLR.[7]

Two feature mask extractors are used for the search of significant masks: the feature mask provider stores the correlation templates, transfers them to the correlator subsystem, receives the standardized correlation result and searches for the correlation maximum. This is done concurrently, i.e. the search for the correlation peak is done within the time required for the correlator subsystem to correlate the next template with its corresponding image window. The actual image window data for the correlation is gained by the image data provider.

The helicopter state observer computes the 4D-algorithms and generates the commands for all other processes by automatically analyzing the results from the extractor and correlation process. The management of all processes as well as the interface to the on-board system is handled by the organizer. Additionally, a display processor is used for supervision.

4. TRACKING, DETECTING AND UPDATING OF FEATURES

The tracking of patterns within a sequence of images is achieved by template matching using a two dimensional cross-correlation. Correlation is a well known technique for comparing already known structures with actual ones. Applied to feature tracking the image data around the estimated position of a feature (called window) has to be

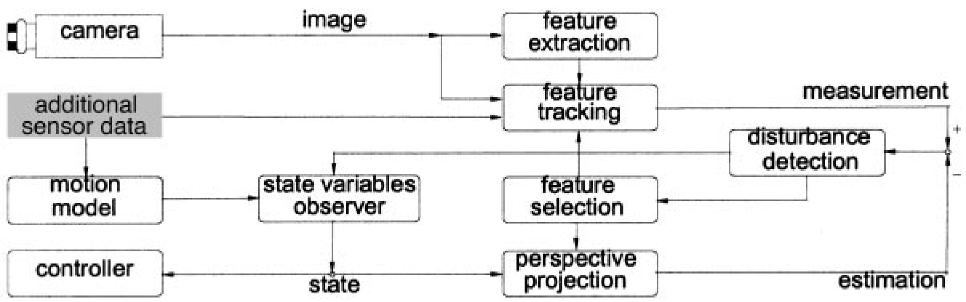

Fig. 2. System design for the general machine vision system.

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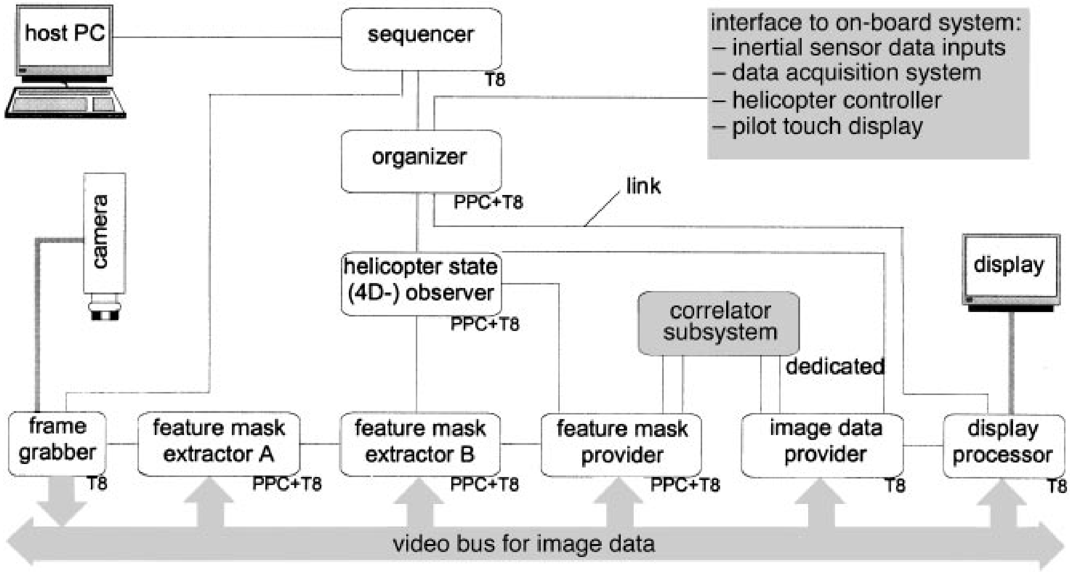

Fig. 3. Machine vision system for the general machine vision system.

correlated with the old image data of the corresponding mask (called template). The coordinates of the maximum value within the correlation result represents the position where the two sets of image data match best. Many correlation functions are known and have been compared, e.g. by Aschwanden.[8] The Pearson function using the Euclidean distance for the standardization shows the best results considering accuracy and reliability (e.g., independence of disturbances like changing lighting conditions). The system does not require an optimal solution for feature tracking and detection since the quality of each feature being used is determined by the 4D-approach. Thus less suited features are excluded automatically from the machine vision process. Nevertheless, in order to enable a tracking of less significant features, fairly huge templates (30×28 pixels) are used.

A feature detection process is used to find image windows which can be used as templates. This feature extraction is performed in three steps: in a first step the image data is filtered through a noise suppression filter; this is done with a Median filter. The advantage of this non-linear filter compared with linear low-pass filters is its ability to remove pixel disturbances without smoothing edges. For the second step Sobel operators are used. The output of these derivative operators is the direction and magnitude of local edges. A local edge is a small area in the image where the local grey levels are changing rapidly. A pre-defined threshold for the magnitude of the grey level discontinuities is used to suppress all areas within the examined image window which do not contain significant information. This threshold depends upon the number of features which are tracked. When no or few features are tracked, then the threshold is set to a small value, thus enabling the detection of less significant features. The localisation of features is the third step. Good feature candidates are defined as being small image windows which allow a tracking in all directions. These candidates typically appear as local places within the image where edges with different orientations meet. The positions and the corresponding original image data of the windows is the required output of the feature extraction process which is used subsequently for feature tracking.

Feature updating is done to cope especially with rotations. Since correlation is not a rotation invariant function, the appearance of the feature masks are rotated according to the measured heading of the flight vehicle.

5. USING THE 4D-APPROACH

Using the 4D-approach means using a prediction and an innovation process for the flight state of the vehicle which frame the actual measurement process. The prediction of the state of the helicopter is based upon the observer results from the innovation, i.e. the actual flight state and its covariance. The predicted estimated state is an input for the measurement process, which calculates the perspective projection for the feature positions. For the observer these are described in a world coordinate system. The estimated flight state is used to tranform the selected feature positions into the image coordinate system, which is a necessary input for the tracking module. Naturally some camera parameters, e.g. the mounted position of the camera, are another input for this calculation. The flight state and the world coordinates of the features are used to evaluate the Jacobian matrix, a sensitivity matrix for the feature positions and orientations with respect to all state component changes. The Jacobian output as well as the estimated and measured position of the features is necessary to bypass the perspective inversion. The method used is recursive least squares filtering through feedback of the prediction errors of the features; this is called innovation of the state. It is based upon the predicted flight state and its covariance. The already mentioned observer results include the positions of the features in a world coordinate system together with their tracking quality. Thus, disturbances can be detected by analyzing all features according to their tracking quality. For every new feature its position has to be transformed from the image coordinate system into the world coordinate system, based upon the actual flight state.

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For a system, which can be described by linear differential equations and which is disturbed by white noise statistics, the Kalman filter provides a recursive least squares scheme which allows optimal recursive state estimation.[2] Inertial sensor data is used to stabilize the machine vision process. The following sensor information is presently used besides the image evaluation: Radio height, pitch and roll attitude as well as heading of the helicopter. This can be extended to include angular rates and translational accelerations. The big advantage of the Kalman filter is its robustness for a changing number of tracked features.

6. RESULTS

The camera operates in the interlaced mode, thus providing two images during each cycle (40 ms) with a resolution of 756×288 pixels for one half image each. The image data is distributed alternately into two buffers on all processors which are connected to the video bus, thus enabling them to evaluate one of these images simultaneously with the arrival of the next image. An 8 mm wide-angle lens is used for the optics. The resolution of the image data is reduced to 45 gray levels via a lookup table on the frame grabber. This guarantees that the 8 bit wide input and 22 bit wide output buffers of the correlator do not overflow. This restriction does not hurt the performance, the human eye too has difficulties to distinguish gray values with a higher resolution.

The pure standardized correlation of a template (30×28 pixels) with an image window (80×52 pixels) takes 5.6 ms using the Euclidean distance. Alternatively, a linear standardization can be used too (taking 4 ms). Five features can be tracked during each cycle (40 ms) since the tracking of five features, including standardization and a complete search of the correlation result for the maximum, takes 34.3 ms (27.2 ms with the linear norm). The calculation of the observer adds at least 0.5 ms for the prediction and 2 ms for the innovation when only 8 state variables are observed, namely the two dimensional position above the ground, the altitude and the heading including their derivatives. The search for new features and the perhaps required rotation of feature masks adds no time since it can be handled independently. The image is divided into 24 overlapping windows for the feature extraction and each processor is able to evaluate one of these windows with a size of 90×75 pixels in less then 30 ms. (The exact timing depends upon the complexity of the image data and the selected threshold). To enable a rotation of the mask, the original stored template has a size of 48×48 pixels.

Several tests were performed to evaluate the system. Offline investigations were carried out using images stored on a video recorded during a test flight for the hover and low speed mode. The real-time tracking of features was validated in a laboratory environment by using the system for measurements of the relative position between the camera and some objects. The camera and/or the objects were shifted while the tracking sensor measured the position on-line.

Further tests with a hardware-in-the-loop simulation demonstrated the closed loop functionality of the system (Figure 4). A ground based simulation computer which is capable of simulating the BO 105 helicopter flight dynamics including inertial sensors and actuators in real-time was used to feed a view simulation, which simulated the view of the downward looking camera.[9,10] The CCD camera was mounted in front of the monitor of this system. The loop was closed by connecting the machine vision system to the on-board control computer. Stimulations of the system were gained by changing the altitude and heading during the hover mode and by disturbing the machine vision sensor through covering manually a part of the image.

Some time histories as they were recorded during closed-loop operation are shown in Figure 5. During the first 500 cycles (20 s, each cycle corresponds to 40 ms) the helicopter was commanded to turn 90 degrees (via a pedal input). Subsequently the altitude was changed (via a collective stick input). During the last 600 cycles (24 s) the machine vision sensor was disturbed several times by covering either the right part or the left part of the camera image with a piece of paper. On two occasions this led to a complete loss of features for a short time. Figure 5 shows in the top diagrams the position in X and Y in the helicopter coordinate system, as it was measured by the machine vision sensor, and compares these results with the position, as it was calculated by the helicopter simulation. Below this the altitude and heading are shown. The bottom diagram gives an impression of the helicopter dynamics during hover by showing the roll and pitch angles.

7. CONCLUSIONS

In initial flight tests it was shown as a proof-of-concept that with a machine vision system it is possible to realise a position hold system for a helicopter in hover above a

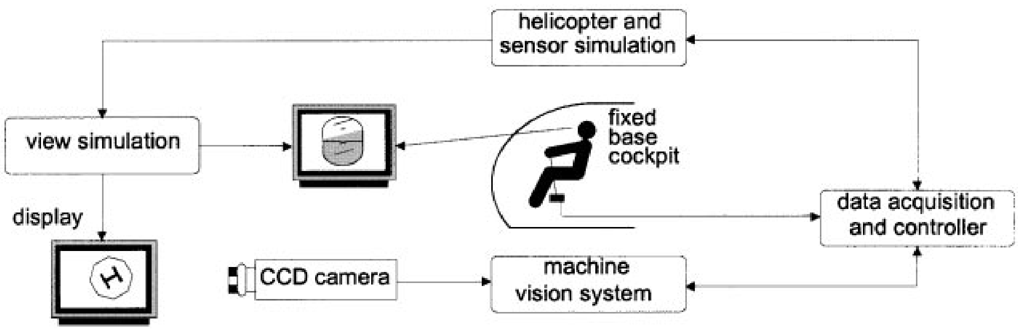

Fig. 4. Hardware-in-the-loop simulation.

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moving target. This leads to the development of a general machine vision system which is able to keep the helicopter above suitable places, on condition that distinct but unknown features can be seen by the camera.

The general machine vision sensor is able to evaluate 25 images per second. Within each cycle up to five features with a template size of 30×28 pixels are matched with image windows of 80×52 pixels. Continuously new features are extracted from the image data, less suited features are identified and excluded from the tracking process. Feature updating is used to cope, especially with rotations. Tests with a hardware-in-the-loop simulation demonstrated the closed-loop functionality of the general machine vision system.

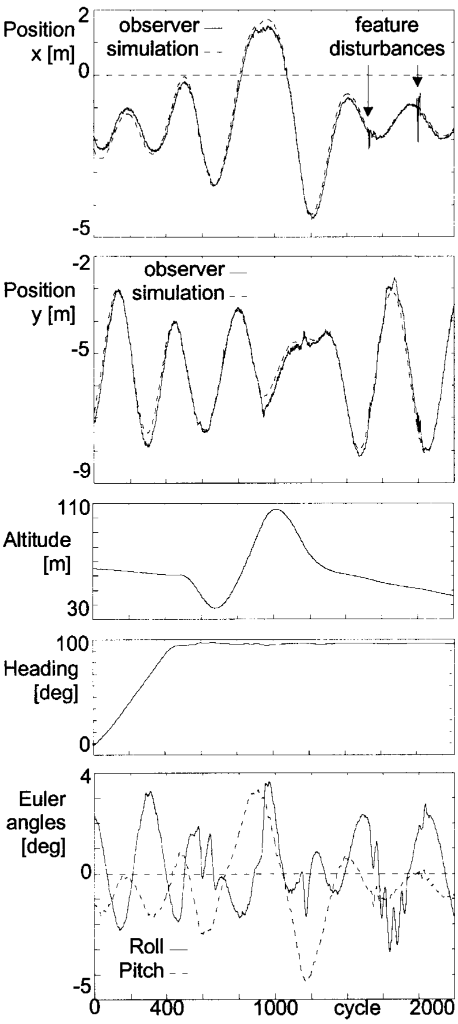

Fig. 5. Time histories from HIL-simulation.

The system can be adapted to alternative imaging sensors and its functionality can be used for image based camera stabilizations or relative position measurements between the camera and two-dimensional objects whose appearance does not need to be known in advance.

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