INERTIAL NAVIGATION SENSOR INTEGRATED MOTION ANALYSIS FOR OBSTACLE DETECTION

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Abstract

There exists a significant need for automatic obstacle detection systems onboard rotorcraft due to the heavy workload demands that are imposed upon the pilot and crew. The current purpose of obstacle detection systems is not to replace pilot functions; rather the systems must augment the pilot's ability for the sake of improving mission safety.

The benefits of such systems are needed in both military and civilian rotorcraft, although, military usage dictates maximally passive (i.e., covert) operation of the system to minimize the probability of rotorcraft detection. Hence, this paper describes a maximally passive system which relies upon the use of passive imagery and the minimal use of an active component (laser radar). The processing of passive imagery yields range measurements to world points ahead of the rotorcraft, and provides scene analysis functions which are capable of characterizing the terrain. Knowledge of vehicle motion as provided by an onboard Inertial Navigation System (INS) improves the robustness of the techniques of passive ranging which include motion analysis and binocular stereo.

In this paper a maximally passive, INS integrated obstacle detection system is described in terms of its processing components, the sensor options which are available, and the requirements which it must satisfy. In addition, high level system implementation issues are discussed.

Introduction

Both commercial and military rotorcraft face significant threats from ground based obstacles such as towers, and power lines. In recent years, considerable attention has been given to the development of obstacle detection systems to combat the danger presented by obstacles. To date, very little work has been done for low flying rotorcraft for which antennas, towers, poles, fences, and tree branches constitute significant obstacles. Currently, without any form of automatic obstacle detection, numerous accidents occur each year, as confirmed by military and industrial reports, and public news items.

There exists a significant need for automatic obstacle detection systems onboard rotorcraft due to the heavy workload demands that are imposed upon the crew.[2] The obstacles which pose the greatest threat to rotorcraft safety are wires and cables suspended in the flight path where the support for such obstacles is obscured. Other obstacles of interest include all forms of vegetation and man-made structures, and the terrain itself (hills, sand dunes, etc.). An obstacle detection system capable of detecting such obstacles within the flight path and warning the pilot (or directly affecting the guidance system), yields obstacle avoidance and improved rotorcraft safety.

The types of sensors used in obstacle detection systems have predominantly been active types (i.e., those that emit energy into the surrounding environment) such as millimeter wave radar and laser radar. Very little work has been done with passive sensors such as TV cameras and FLIR sensors. Regardless of the type of sensor used in the obstacle detection system, the system must be able to compute the relative range to world objects and measure or infer the size of all objects which are classified as obstacles. In general, a relative range map to all world features within an area surrounding the rotorcraft's direction of motion must be provided. Given the range map, obstacles can be detected and navigation solutions for obstacle avoidance can be computed.[3]

In what immediately follows, a maximally passive system for obstacle detection which benefits from the use of inertial data is described. Later, the sensor options are briefly discussed, sensor fusion needs are mentioned, and some critical system requirements are presented and their affect on system implementation is discussed.

Passive Systems for Obstacle Detection

In commercial rotorcraft applications a requirement for a covert obstacle detection system does not exist, although the cost of a fielded system must be low. In noncovert applications all types of active sensing are available for use in obtaining range data. The most obvious types of active sensing are MMW radar and laser radar. These two types of sensing have the spatial resolution necessary to detect small obstacles such as wires. In particular, MMW radar sensors are inexpensive such that the cost of the overall system can be kept affordable.

In military applications, there is a strong need for the rotorcraft to be covert such that the probability of mission success/safety is kept high. Any source of radiation emanating from the rotorcraft announces the rotorcraft presence and sacrifices covertness. Hence, passive sensors are needed in military obstacle detection systems. In addition, military applications require more elaborate forms of pilot and guidance interface because the military rotorcraft pilot often becomes excessively burdened by performing other mission tasks. This is especially true when the rotorcraft is flying at low altitude, in particular when the rotorcraft is in the Nap-of-the-Earth (NOE) flight regime (see Figure 1).

The covert systems rely on the use of passive sensors which have the potential to be much less expensive and easier to maintain than active sensors. The approach to obstacle detection that is presented in this paper employs motion analysis of 2-D imagery provided by a passive sensor.

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Motion analysis of imagery obtained during vehicle travel is used to generate range measurements to world points within the field-of-view (FOV) of the sensor, which can then be used to generate a range map which can be used to detect obstacles.

The approach to motion analysis presented herein is feature based. As will be discussed in the next section, distinguished world objects are detected and extracted as image features in each image frame. Then a matching algorithm is used to link the image features (that occur in consecutive image frames) which correspond to the same world object (or part/feature of an object). Given the matching results, and knowledge of sensor motion, range can be computed to world objects. For range to be computed to a world object, it must have had its corresponding image features tracked through multiple (at least two) image frames.

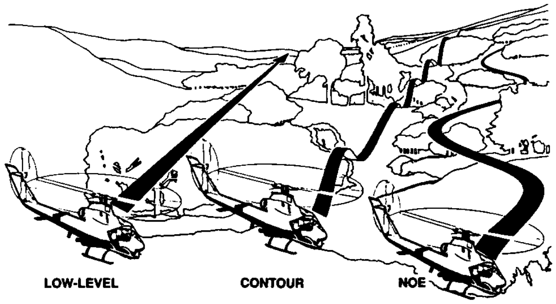

Figure 1: The three broad categories of rotorcraft flight are Low-Level, Contour, and Nap-of-the-Earth (NOE).

Inertial Data Integration

Many types of existing rotorcraft contain an inertial navigation system (INS) which can be utilized to greatly improve the performance of motion analysis techniques and make them useful for practical military and civilian applications. An INS provides very accurate measurements of the accelerations, velocities (both rotational and translational), and instantaneous attitude of whatever platform contains the INS. The use of inertial data is the keystone of our approach to motion analysis.

The motion analysis approach taken by the authors, makes use of INS data to improve distinguished feature selection, matching of the distinguished features, and the subsequent temporal tracking, range computation, and obstacle detection. Knowledge of sensor motion enhances motion analysis processing in two fundamental ways: it removes the effect of sensor rotation and therefore reduces the problem of feature correspondence, and it allows the focus of expansion (FOE), the point of intersection of the sensor's velocity vector and the sensor's image plane, to be computed (if a sensor model is provided) rather than having to estimate the FOE from image measurements.

Two techniques for inertial data integrated motion analysis have been developed by the authors of this paper. Both techniques employ similar steps in the processing at a high level but they differ in their implementation. The block diagram of the INS integrated motion analysis algorithm is shown in Figure 2. A high level block diagram of a maximally passive obstacle detection system is shown in Figure 3. In the following, the processing steps shown in Figure 2 are discussed. and the functions in Figure 3 are briefly described.

The input data to the algorithm consists of a sequence of digitized video or FLIR frames that are accompanied by inertial data consisting of rotational and translational velocities from which sensor position and instantaneous attitude can be computed.

The features within the imagery (TV or FLIR) that are most prominent and distinguished mark the world objects to which range measurements will be made. These prominent world objects are by definition those objects whose image features have the highest promise of repeated extraction within multiple consecutive frames.

The goal of feature derotation is to reduce the motion analysis problem to that of purely translational motion. In other words, derotation makes it seem as though the position of the image plane during frame acquisitions does not vary in terms of its attitude (i.e., the image plane experiences only translational motion). In the second approach, no derotation is performed. The current location of the image feature together with the vehicle parameters from the INS are used in

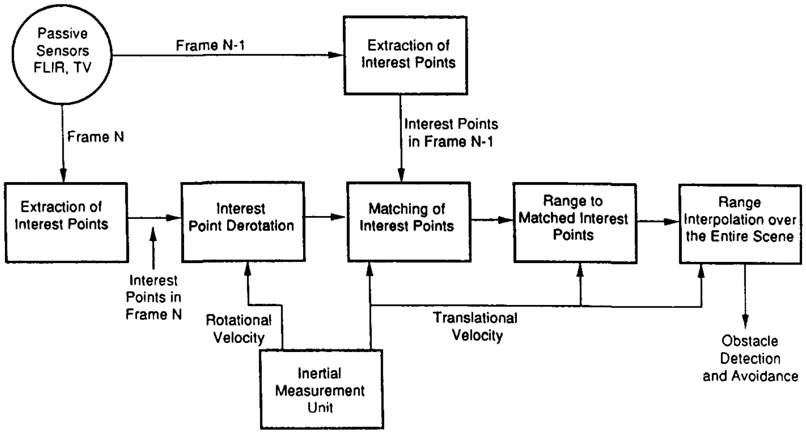

Figure 2: As illustrated, the inertial data integrated technique of motion analysis makes motion analysis feasible and robust.

an extended Kalman filter to predict the feature location in the next frame. The ability to predict the feature location simplifies the matching problem. The algorithm is made robust by discarding features which do not follow the geometrical behavior of objects in the outside world. The Kalman filter is also used to estimate the range given the feature location in successive frames. In either case, the end result is that for a processed sequence of imagery, the image planes which acquired the imagery are all made to be effectively parallel. Figure 4 illustrates the case of purely translational motion. The benefit of derotation is also illustrated in Figure 4 where the superimposed image planes show that image features radiate away from the FOE over time (also note the definition of FOE for this simple case of a pin-hole camera model).

The problem of matching is greatly simplified after derotation is performed. As previously mentioned, the image features radiate away from the FOE. Hence, the matching process searches for a match to an image feature in the current frame, f_i, by scanning along the line that joins the FOE and f_i. A variety of metrics have been incorporated into our matching algorithms to account for error in derotation, feature extraction, and the occurrence of multiple candidate matches.

Once matched, a pair of image features can be used to compute range to their corresponding world object. The range equation used for this computation is shown in Figure 5 along with the geometry used in deriving the range equation (note that the figure shows a moving object instead of a moving sensor to simplify the geometry). The range equation

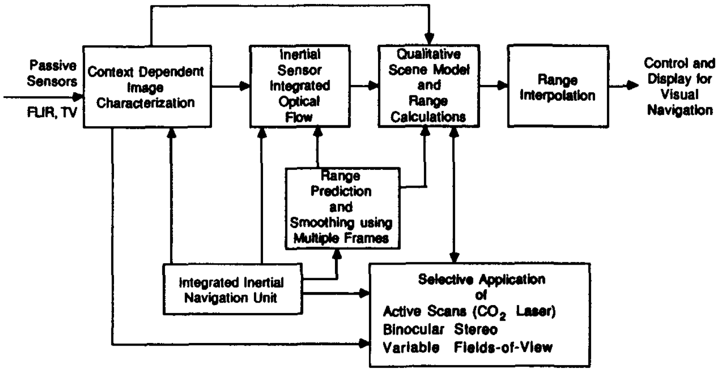

Figure 3: Inertial data integrated motion analysis and scene analysis using both passive and selective applications of active sensors, provide obstacle detection and increased effectiveness of rotorcrafts in all scenarios encountered during low-altitude flight.

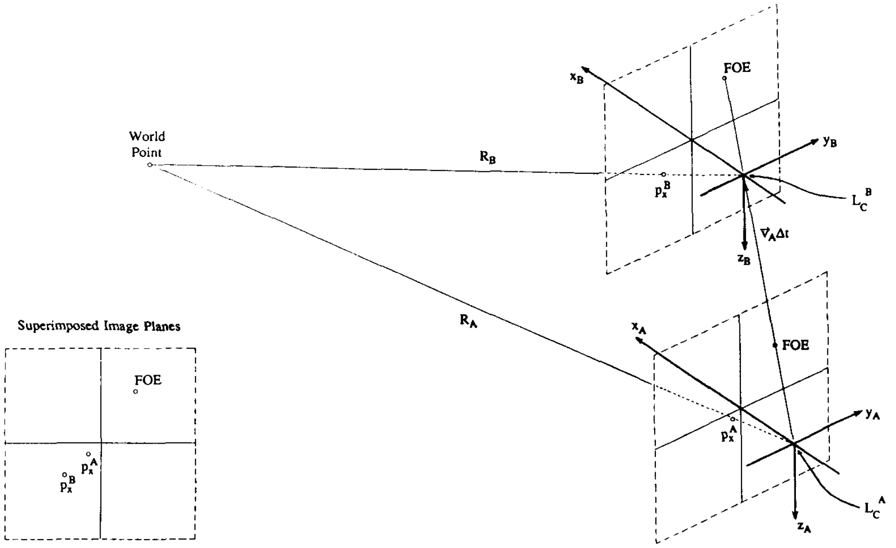

Figure 4: The geometry of image acquisition during purely translational sensor movement is shown here. The superimposed images planes are shown to illustrate the linearity of the three image points: the FOE, and the projection of a world point onto two successive locations of the image plane.

depends on the distance between image planes, $\vec{V}\Delta t$, and the *image plane locations* of the FOE, and the image features.

The previous paragraphs have discussed most of the functional blocks in the system diagram in Figure 3, but *Context Dependent Image Characterization* and *Range Interpolation* have yet to be described. The context dependent image characterization is a process in which scene analysis is performed for the purpose of generating a scene model of the environment through which flight is occurring. By a 'scene model' we mean a labeling of the sensed image in which the various segments are labeled as to their respective types of terrain (e.g., sky, road, and grass). This scene analysis process is applied to each frame and results in a temporally evolving, spatial model of the scene. The scene model is of assistance in the intelligent interpolation of the measured range data, and the intelligent selection and distribution of image features throughout the sensors' field of regard.

Range interpolation is required by the obstacle detection system for the creation of a dense range map from the potentially sparse range samples obtained from the various types of ranging incorporated into the system. The required density of the range map is to facilitate the extraction of range discontinuities, and aid the process of determining a 'clear flight path.' The technique of interpolation used to create the dense range map should not cause false range contours having range too short or too far. Hence, high order polynomials are to be avoided.

For more detail on the two implementations of inertial data integrated motion analysis, refer to the papers by Roberts and Bhanu[1,4] and Sridhar.[5-7] The work performed by the authors on INS integrated motion analysis algorithms for obstacle detection has included the testing of the algorithms on limited data sets (i.e., image sequences) that have a limited amount of ground truth with which to measure algorithm performance. The range measurements that are made by motion analysis algorithms have been compared to the available ground truth and have shown significant promise.

Sensor Fusion

Two fundamental forms of passive ranging are available: range from motion analysis, and range from binocular stereo. Up to this point in the paper we have considered only motion analysis but binocular stereo can be used to nicely complement a motion analysis system.[8]

The combination of motion analysis and binocular stereo techniques of passive ranging enhances obstacle detection sytem performance and robustness in three key ways:

- generates a more dense collection of range samples that cover the field-of-regard (FOR) covered by the sensors,
- improves the accuracy of range samples (i.e., when range to a feature is computed by both techniques, range blending can occur), and
- the combination extends the operational domain of the obstacle detection system (i.e., the system performs even when the rotorcraft is stationary).

The two techniques differ in such a way that a disadvantage in one technique is nullified by the other. The following table itemize the features of each passive ranging technique:

Motion Analysis	*Binocular Stereo*
One sensor	Two sensors
Requires sensor motion	No motion necessary
Error prone near FOE	Uniform accuracy over FOV
Best at FOV edge	Functions only where the FOV's overlap (poor at FOV edge)

The block diagram in Figure 3 identifies that the system uses a laser range sensor. The use of such an active sensor is approved only for intermittent use in a narrow FOV surrounding the direction of motion. The sensor's restricted FOV is used only to clear the immediate flight path of obstacles too small to be detected with the passive sensors which may lack the required resolution (depending on their FOV

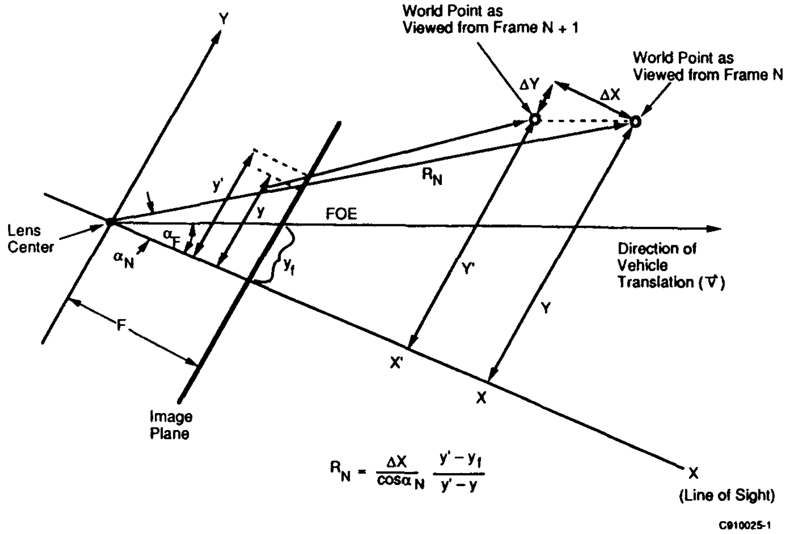

Figure 5: The geometry involved in the range calculation is illustrated here. The figure shows the imaged world point in motion rather than the sensor which simplifies the geometry for deriving the range equation.

and focal lengths). The active sensor scans in a simple elliptical pattern with a narrow FOV to minimize system cost and minimize rotorcraft exposure.

The range samples obtained from the three forms of range measurement are made in as many as three different coordinate systems located at different locations on a rotorcraft. The fusion of the range measurements can be combined with simple trigonometric functions once the relative locations and orientations of the three coordinate systems are known (through measurement and/or sensor calibration).

System Requirements and Implementation

In this section a brief discussion of system requirements, their affect on system parameters, and some system implementation issues are presented.

Many factors contribute to the definition of obstacle detection system requirements:

- the rotrcraft on which the system will be installed,
- the mission being flown and the flight regime in which flight is occurring, and
- the pilot's response time and the processing time required by the obstacle detection system,

This list is far from complete but it is sufficient to illustrate the impact that the operational domain will have on the system requirements which will yield a set of basic system parameters.

Different rotorcraft have different limitations on the types of maneuvers that they can perform. In particular, the maximum g-loads that a rotorcraft can sustain, limit the types of maneuvers which the rotorcraft can perform. Hence, the rotorcraft on which the system will be installed is very important to the system definition because the maneuvers to be performed will determine the sensor FOV requirements.

The regime in which flight is taking place (low-level, contour, or NOE) bounds the speed of flight and therefore the range of maneuvers which can be performed. For example in NOE flight the average speed is less than 40 kts which for a given lateral acceleration limit, a_L, will allow much sharper turns than is the case in contour flight where average speeds approach 80 kts (radius of turn = v^2/a_L). This leads to the need for a wider system FOV within which obstacles must be detected because at any time the need may arise to change course in any physically allowable direction. All potential directions of travel should be 'covered' by the system. Hence, one can see that system FOV is determined by the flight regime and the corresponding speed.

Finally, the *look-ahead* time, which we define to be the addition of the pilot's response time and the processing time required by the system, is critical in setting the minimum range at which obstacles must be detected and reported by the system. The minimal amount of pilot response time is 6 seconds with the nominal amount of time being 10 seconds. The system processing time ideally will be equal to one image frame acquisition interval plus one interval of latency. Hence, the look-ahead time of the system will be in the range of 6 to as high as 11 seconds.

The minimum range at which obstacles can be detected is the product of speed and look-ahead time which needs to be greater than 120 meters during NOE flight with a 39 kts (20 m/s) airspeed. This minimum range determines the maximum acceptable resolution of the sensors. The actual sensor resolution must be much greater to detect small obstacles such as wires, but at least an upper bound, system requirement on sensor resolution is clearly defined.

In implementing and fielding an obstacle detection system, a variety of issues must be addressed: pilot interface issues (e.g., information display format and the type of displays), integration and interface with other rotorcraft systems (e.g., INS and displays), sensor mounting considerations, and computational/computer needs. A preliminary study of these issues has been performed to date but much has yet to be done. Plans are being made to implement the inertial data integrated motion analysis technique as described in this paper within hardware that is capable of executing the algorithm in real-time. Such flyable hardware will allow extensive testing of the passive ranging technique and will be a platform in which the computational needs of the algorithm can be assessed. Both items are important steps in system evolution into a fielded system.

Summary

This paper has described a maximally passive system for obstacle detection and avoidance designed for rotorcraft. The described system when implemented and installed on rotorcraft will result in fewer rotorcraft collisions, and improve rotorcraft mission performance. In addition, the development of an automatic obstacle detection system that is capable of computing the necessary guidance and control actions to avoid obstacles, is an important step toward totally autonomous vehicle navigation.

The technologies that underlie the maximally passive system described in this paper are not at the point where the system can be fielded. Future efforts toward such systems must touch upon a variety of topics:

- additional algorithm development work (e.g., motion analysis, binocular stereo, and sensor fusion algorithms),
- data collection efforts (to generate enough data to validate the system's performance),
- the study of system implementation issues, and
- system integration issues (e.g., intersystem and pilot interface).

The efforts of the authors will continue along these lines in upcoming years.

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