A System For Obstacle Detection During Rotorcraft Low-Altitude Flight

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ABSTRACT

Airborne vehicles such as rotorcraft must avoid obstacles such as antennas, towers, poles, fences, tree branches, and wires strung across the flight path. This paper analyzes the requirements of an obstacle detection system for rotorcrafts in low-altitude Nap-of-the-Earth flight based on various rotorcraft motion constraints. It argues that an automated obstacle detection system for the rotorcraft scenario should include both passive and active sensors. Consequently, it introduces a maximally passive system which involves the use of passive sensors (TV, FLIR) as well as the selective use of an active (laser) sensor. The passive component is concerned with estimating range using optical flow-based motion analysis and binocular stereo in conjunction with inertial navigation system information. Experimental results obtained using land vehicle data illustrate the particular approach to motion analysis.

1 INTRODUCTION

In recent years considerable effort has been put toward the detection of obstacles that present themselves to ground vehicles. Using primarily active sensors, such as a laser scanner, obstacles (like fence posts, rocks, vegetation) within the field of view (FOV) of the vehicle's sensor are detected. Passive sensors such as a TV camera are also being used to detect obstacles for ground vehicles. However, very little work has been done to date for the detection of obstacles for a rotorcraft performing a low-altitude flight. *Obstacles*, in the context of a rotorcraft, are defined as physical objects -- natural or man-made -- that present a danger of collision to the rotorcraft. In contrast, *hazards* are situations that expose the rotorcraft to danger or adversely affect the mission in some other way. For both commercial and military rotorcrafts flying at low altitudes, antennas, towers, poles, fences, tree branches and wires strung across the flight path constitute significant obstacles. Automatic detection of these obstacles and their display to pilot and/or automatic guidance and control action triggered by such detection, would help conserve the pilot's attention for the mission tasks, thus contributing to mission success and most importantly saving lives. The problem of obstacle detection would become especially serious in a single-pilot rotorcraft where the pilot's attention must be concentrated on mission tasks such as attack and scout.

During terrain flight, military rotorcraft uses vegetation, terrain, and man-made objects to conceal itself from the enemy's visual, optical, or electronic detection systems by flying close to the earth's surface. This mode of rotorcraft flight is known as the Nap-of-the-Earth (NOE) flight (the remaining categories are the low-level and contour flights) and is the most demanding on the crew. During NOE flight, air speed (0 to 40 knots) and altitude (under 100 feet) vary according to terrain, enemy situation, weather, and ambient light. Commercial rotorcraft share most of the same obstacles and hazards of low-level and contour flight with military rotorcraft.

Presently, crew members rely on a sophisticated combination and fusion of sensors, "smart skin" antennas, computers, and displays in order to accomplish their mission under conditions of night, reduced visibility, bad weather, or NOE operations in a hostile environment. The state-of-the-art in NOE army rotorcraft flight involves the use of FLIR imagery for the co-pilot and night vision goggles for the pilot.

Automated NOE flight to relieve pilot work load and to allow single pilot mission capability requires the following:

- A sensor suite that is able to map out the region ahead of the rotorcraft determining the obstacles that are of concern.
- A trajectory generation algorithm that defines the optimum flight path through that region considering threats, way points, and other constraints.
- An advanced flight control system that considers maneuverability, stability, and robustness.

The sensor system for mapping out the region ahead of the rotorcraft is a formidable challenge and is the focus of this paper. It is the key issue that needs to be overcome for the single-pilot, automated NOE capability to be useful in practical situations.

The difficulty arises in selecting an automatic obstacle detection technique that is dependable and robust under various scenarios such as day/night/adverse

This material is based upon work performed at Honeywell and supported by NASA under contract NAS2-12800. The authors would like to thank Banavar Sridhar and Dallas Denery of NASA Ames Research Center for their guidance and support of this work.

0-8186-2840-5/92 $03.00 © 1992 IEEE

weather conditions, and can be implemented and interfaced with the pilot/rotorcraft system without unduly excessive size, power, and weight demands on the rotorcraft. The technique must also have graceful degradation, instead of total failure, under conditions of limited operability. Moreover, the detection technique should preferably be covert to minimize the threat to the rotorcraft and the pilot.

Several automated techniques have been developed that promise passive detection of obstacles, based on passive ranging and feature-based spatio-temporal analysis of TV imagery. Unfortunately, most of these methods have extremely unrealistic constraints imposed on the image formation process to make them work. The biggest sources of errors or reliability problems are sensor motion and incomplete/ambiguous information in the sensed data (imagery). Therefore, these techniques are hardly reliable in practical applications such as in a rotorcraft flight. Also, not many of these techniques have been developed for day/night sensors such as Forward Looking Infrared (FLIR). Active sensors such as Millimeter Wave (MMW) and CO_2 laser can detect obstacles such as wires, but the continuous operation of these sensors betrays rotorcraft covertness.

This paper describes a *maximally passive* system for obstacle detection that can improve the safety of rotorcrafts during low-altitude flight. In Section 2, we review the past research related to obstacle detection. Section 3 discusses the requirements demanded of an obstacle detection and avoidance system for rotorcrafts performing NOE flights. Section 4 describes an innovative maximally passive obstacle detection system that has not been reported in the literature. In Section 5, we present the results of our obstacle detection system operating on outdoor imagery coupled with inertial data. Finally, Section 6 provides the conclusions.

2 PAST RESEARCH

Obstacle detection (for both autonomous land vehicles and rotorcraft) using passive sensors rely on two fundamental techniques for ranging: binocular stereo and motion stereo (optical flow). Binocular stereo employs two laterally displaced sensors. These stereo methods have been widely studied for determining range passively.[1,8] To a first approximation, the error in binocular stereo range measurements is directly proportional to the positional error of the matches and inversely proportional to the length of the baseline[1] (lateral displacement between the sensors). However, the longer the baseline is, the more difficult it is to ensure that a large number of points are visible in both images simultaneously.

Motion stereo utilizes one sensor in motion from which image frames are collected at fixed intervals of time. By observing the amount of image plane-motion that a particular world point exhibits between frames (i.e., optical flow) and using the knowledge of sensor motion, range to the world point can be computed. The estimation of the optical flow can be based on the derivatives (gradients) of the image brightness function when suitable constraints are applied to the flow field.[5] One fundamental limitation of these gradient-based methods is that they are highly sensitive to noise. Furthermore, theoretical analysis has shown that there is a direct conflict between various constraints imposed on the flow field.[7] In particular, it is shown that errors due to instability of solutions of the required systems of equations are inversely related to the size of the neighborhood used for flow smoothness constraints. However, increasing the size of the neighborhood violates the flow smoothness constraint.

An alternate approach to the estimation of optical flow is to match image features (points, edges, regions or boundaries) between a temporal sequence of two or more images.[2] The motion between frames can be decomposed into translational and rotational components. The final (usually the second) image in the sequence can then be derotated to achieve a relationship approximating pure translation between the first and final images. In the case of pure sensor translation in a stationary environment, every point seems to expand from one particular image location termed the *Focus of Expansion* (FOE). This method yields relatively sparse set points for which range values are obtained unlike the gradient-based method. However, range to other image points can be estimated using interpolation procedures. Issues raised here include accurate frame to frame correspondence, accurate FOE location, and the magnitude of interpolation ambiguities.

Although the aforementioned techniques comprise the majority of methods used in passive ranging, various other approaches have also been suggested.[6] Bowman and Gross[4] have proposed a method for passive ranging to targets using data from two different aircrafts, which is inapplicable to the rotorcraft low-altitude flight scenario. Techniques based on Kalman filtering have also been developed for general motion and passive ranging.[11]

Obstacle detection is also possible using active sensors such as laser and Millimeter Wave (MMW) radar systems. Currently, a number of 3-D laser scanners using phase detection technology are available.[3,10] One such sensor, developed for autonomous vehicle navigation, has a field-of-view of ±40° horizontal which covers depression angles from 15° to 45° with a range resolution of 8 centimeters. More advanced systems with multiple lasers operating at multiple frequencies (in the visible, near infrared, and shortwave infrared wavelengths) and having a range resolution of 2 centimeters are also under development.

Thomson CSF is developing a compact MMW radar system (Romeo 2) which uses a 3 second-scan over a 90° sector to detect hazardous objects. Prototype systems have detected 3 millimeter diameter high tension cables at ranges of 1000 meters in foggy weather. The system is designed to detect similar objects with small cross sections.

Unfortunately, active systems provide good obstacle avoidance capability at the price of increased danger to the crew and the vehicle, regardless of whether the active system is based on laser or MMW radar ranging. Consequently, their use should be contingent on the capabilities of passive obstacle detection/avoidance technology in near and far future systems.

3 REQUIREMENTS FOR AN OBSTACLE DETECTION SYSTEM

In this section, we analyze the requirements of an obstacle detection system for a rotorcraft during NOE flight. First, we describe the pertinent rotorcraft maneuvers. Next, we analyze these basic maneuvers and specify the kinds of requirements that must be satisfied at the system, sensor, and algorithm levels. Finally, we discuss the various system options with respect to these maneuvers.

3.1 Rotorcraft Maneuvers

A rotorcraft can engage in three different kinds of maneuvers during NOE flight: longitudinal, to decelerate to a quick stop; lateral, go around an obstacle; and vertical (*pull-up* and *pushover*), to go over or under an obstacle. Besides, it may need to turn corners. Maneuvers also include deviations in rotorcraft attitude involving, in particular, the aft section of the fuselage (tail rotor). The position of the tail rotor in relation to obstacles is important, as a tail rotor strike could result in an uncontrollable spin.

The main considerations that need to be accounted for during the NOE flight are,

- Avoid obstacles on all sides of the rotorcraft and some nearby obstacles (overhanging branches);
- Minimize or avoid hazards such as vertical pull ups when lateral movement is possible, the use of active sensors (intelligent application), and the adverse effects of downwash;
- Move as rapidly and safely as is possible.

3.2 Maneuver Imposed Requirements

In this subsection, we describe the various requirements imposed on the obstacle detection system by four types of rotorcraft movements -- longitudinal, lateral, vertical, and turning corners.

Longitudinal maneuvers -- The key factor in longitudinal maneuvers is the *sensor resolution* required for obstacle detection. The sensor resolution must be sufficiently high to allow for the detection of an obstacle. Objects that fill only one pixel cannot, in general, be detected because of blurring and low signal-to-noise ratio. Depending on the scene background, contrast, and noise, anywhere from 2 x 2 to 5 x 5 pixel coverage on the object will be needed. Linear objects like wires or moderately straight branches are an exception in that one pixel in the transverse axis is often sufficient for recognition, given many pixels of coverage along the wire or the branch.

It is important to note that the longitudinal stopping maneuver becomes necessary only when the environment traps the rotorcraft, i.e., disallows lateral or vertical maneuvers. Objects of pixel size -- twigs, branches, and the like -- are attached to larger objects and do not float freely in space blocking the path of the rotorcraft. However, wires can easily block the path of a rotorcraft and under some circumstances demand a full stop. Consequently, the ability to obtain up to 5 x 5 pixels on an isolated obstacle is not a requirement for longitudinal stopping whereas obtaining l x n pixels on wires is an important requirement. It is to be noted that this latter criterion places severe demands on a wide FOV passive system.

Lateral and vertical maneuvers -- *Field of view* dimensions is the key consideration in both lateral and vertical maneuvers. There are two important FOV configurations: static, in which FOVs are fixed because the sensors are rigidly attached to the rotorcraft; and gimballed, in which FOVs are flexible because the sensors are mounted on gimbals. A gimballed configuration is valuable when a maneuver is anticipated. In this configuration, the sensor is pointed in the direction of the lateral or vertical acceleration to obtain a better survey of the obstacles lying in the region of the expected trajectory. The key question in determining the system requirements for lateral and vertical maneuvers is, how to infer about the peripheral objects when every sensor has a limited field of view?

To address the above question, we observe that there are three possible options. The first option is *knowledge-based*, i.e., one can only trust what one knows. Suppose, the obstacle detection system employs a low resolution wide FOV passive sensor and a high resolution narrow FOV active sensor, and no wires are observed by the narrow FOV active system; a knowledge-based conclusion will be the absence of wires. In reality, there may still be unseen wires outside that narrow FOV missed by the wide FOV passive system because of its low resolution.

The second option is *inference-based*, i.e., one can always trust what one infers. For example, detecting and ranging to wires in a narrow FOV allows a reasonable and cautious inference of their presence outside the FOV. Not detecting wires in a narrow FOV may imply their absence in the FOV periphery. The presence of towers, posts, poles, etc., in any part of the system FOV is a trustworthy indicator of the presence of wires.

The final option is *context-based*, i.e., the confidence one has in an inference is a matter of context. This is the most reliable option. In some scenarios valid inferences can be drawn, in others their truth is only probable. For example, in an open clearing, the absence of telephone poles, posts or towers (as determined by a wide FOV passive sensor) dependably indicates the absence of wires throughout the wide FOV.

There are several variables which serve to constrain the extent of lateral and vertical motion maneuvers: (1) *Broad Trajectory* -- It is important to know in advance the location of obstacles over as broad a FOV as possible, especially to take advantage of the lateral maneuverability of the rotorcraft; (2) *Obstacle Avoidance* -- Due to finite spatial resolution and finite range accuracy, the 3-D positions of obstacles are uncertain. With large 3-D uncertainties, the maneuvers must involve either larger banking and climbing accelerations or lower velocities or some combination; (3) *FOV Dimensions*; and (4) *Rotorcraft Acceleration Limits*. The first constraint requires as large a FOV as possible (even for the narrow, active FOV). The second constraint leads to a small, high resolution FOV for accuracy in the image plane and range accuracy. The third constraint encourages a large FOV, and the fourth constraint restricts the required size of the FOV.

Turning corners -- The FOV must be large enough to see obstacles that lie along any curved trajectory resulting from a lateral maneuver. In other words, the sensor must be able to see every place that possible (immediate) maneuvers can take the rotorcraft, otherwise, rotorcraft maneuverability will be wasted. This FOV will be necessary when the system cannot anticipate which way the rotorcraft will maneuver. Such situations occur when the rotorcraft comes out of a narrow gap into a wide opening or when it turns a corner. In these situations, it does not matter whether one has a static configuration or a gimballed configuration, because a gimbal uses the anticipation of a maneuver to direct the sensor and in these situations there is no anticipated maneuver, only a set of possible maneuvers.

3.3 Sensor Suite Options For Different Maneuvers

In the following, we discuss various sensor suite options with respect to longitudinal, lateral, and vertical stopping and corner negotiating maneuvers.

Motion Stereo -- With a purely *motion stereo-based* system, one must obtain the range to an obstacle in addition to detecting it. Since range-from-motion is not computable at the FOE, a purely motion stereo system will fail in exactly the direction which is most relevant to the rotorcraft; hence its performance will degrade severely near the FOE. Interpolation of ranges near the FOE might help, but in general cannot be trusted. Thus, pure motion stereo-based passive ranging is not suitable by itself for *longitudinal* maneuver. The use of a narrow FOV, high resolution passive sensor would decrease the angular region of range uncertainty near the FOE and would allow for a more trustworthy interpolation of range estimates from surrounding data, but would lose important off-axis information which is crucial for *lateral* and *vertical* maneuvers.

Binocular Stereo -- A *binocular stereo* system by itself, is a possibility in the sense that it can provide range estimates anywhere within the stereo FOV, but it is not a good choice for ranging to wires (for example, a very small, high resolution FOV ~4° will be needed to detect wires 3mm thick at 40m distance). The reason is that it is difficult to solve the correspondence problem with wires because of the lack of features on these objects. Besides, other objects such as branches may occlude parts of a wire from the sensors. Also, the wire and the baseline of the stereo platform must not be parallel to each other so that a significant disparity may be observed in the wire's image projections to compute the range reliably. This, in general, cannot be guaranteed.

Active Sensor -- In general, lasers and MMW radar systems are able to detect and accurately determine the range of terrain obstacles. For all weather conditions, a MMW radar is better suited than a laser radar. For terrain following and obstacle detection and avoidance, laser radar is preferred because it is less susceptible to detection by enemy and has the necessary resolution to detect objects like thin wires, particularly at oblique angles. Laser scanners are known to have slow scan rates and require large FOV's for successful rotorcraft navigation. However, the sole use of an *active system* (laser or MMW) introduces a hazardous situation (detection by the enemy) and violates the philosophy of making maximal use of passive technology.

Motion Stereo and Active Sensor -- A combination of a large FOV *motion stereo* system and a small FOV *active sensor* can provide ranges near the FOE for *longitudinal* trajectories. A large FOV helps in thorough understanding of the scene that results in avoidance of side obstacles (including the ground), enabling of tight turns (full rotorcraft maneuverability), and increased *lateral* and *vertical* trajectory options (for it is better to move laterally than to stop or go over obstacles in NOE flight). This is the most natural option, because motion based ranging provides its best results away from the FOE which is just what a wide FOV will provide. An active sensor with a narrow FOV will be able to detect small objects like wires near the FOE.

Binocular Stereo and Active Sensor -- A hybrid *binocular stereo-active sensor* system is also possible. In theory, the binocular stereo system could range to everything but wires. It would merely detect wires during segmentation (say) of the images. Upon detection the passive stereo system could activate a laser to scan the wires to obtain range. To do this, a laser ranger must illuminate at least two points on the wire. These two points could also be used by the stereo system as correlation points. Such a hybrid system would minimize the use of the active component, thereby, satisfying covert operation.

Motion Stereo and Binocular Stereo -- A wide FOV *motion stereo* and a narrow FOV *binocular stereo* can be combined to overcome the limitations of each approach as discussed above. However, the binocular stereo component is not capable of detecting small wires. Also, joint inertial stabilization of the two laterally displaced sensors is required to account for even the slightest vibrations that otherwise would significantly reduce (in size) the overlapping part of the two FOV's and would increase the possibility of mismatches, e.g., uncorrected vibrations (up to 1°) would lead to range errors on the order of 30%. Besides, the integrated system substantially increases the hardware and algorithm complexities.

Motion Stereo, Binocular Stereo, and Active Sensor -- The most complex system would involve *binocular stereo*, *motion stereo*, and *active sensor* systems. A large FOV motion stereo would benefit *lateral* and *vertical* maneuvers. A narrow FOV binocular stereo could be set to cover the motion-blind spot, thereby providing higher resolution (spatial and range) near the FOE than would be possible with a wide FOV stereo; thus, *longitudinal* maneuvers would be facilitated. Besides, given a narrow binocular stereo FOV that can yield fairly accurate range estimates, the active system would not be required to perform a dense scan of the FOV for obstacles other than wires, whereas, with a hybrid (motion or binocular) stereo-active sensor system this dense scan would be more likely.

The number of sensors in such a system becomes problematic. Four sensors are required to support the narrow FOV stereo subsystem, the wide FOV motion subsystem, and the active subsystem. Conceivably, the stereo subsystem could switch periodically from the narrow to the wide FOV, to be used for both narrow FOV stereo and wide FOV motion-based ranging. Another difficult option, setting one of the stereo cameras to a wide FOV and the other to a narrow FOV, would lose the narrow FOV resolution and thus would be ineffective. The wide FOV binocular stereo, wide FOV motion stereo, and active sensor subsystems would provide redundancy and trustworthiness. This may be absolutely necessary and not a mere luxury in the presence of low contrast, highly occluded vegetation.

4 A MAXIMALLY PASSIVE OBSTACLE DETECTION SYSTEM

Based on the analysis described above, we have developed a maximally passive system, called ODIN (Obstacle Detection Using Inertial Navigation), for obstacle detection and avoidance. It is based upon an inertial navigation system (INS) integrated optical flow algorithm and selective applications of binocular stereo and laser radar (LADAR) ranging. First, a brief description of the maximally passive system is given. This is followed by the discussions of the INS integrated optical flow algorithm.

4.1 ODIN System Descriptions

The schematic description of the ODIN system is illustrated in Figure 1. Our technique for obstacle detection and avoidance is maximally passive in that we uniquely combine data obtained from a INS into the optical flow computations. The technique also involves the use of context dependent image characterization, and the selective application of binocular stereo (passive), and laser radar (active) ranging.

The incorporation of inertial data into the optical flow algorithm makes our approach robust. Traditional techniques suffer greatly from errors in the estimation of the location of the FOE and from errors in matching world points between frames. The inertial data enable our algorithm to compute (almost) the exact location of the FOE and remove the effect that sensor motion (roll, pitch and yaw) may have upon the imagery, thus the motion is effectively reduced to pure translation. When the motion consists solely of translation, the task of world point matching is greatly simplified.

The passive ranging technique of binocular stereo is most accurate near the center of the FOV (where the FOE is located most of the time) and becomes less accurate near the periphery. In addition, the binocular stereo approach can function even when there is no motion, e.g., the vehicle is stopped or hovering. Hence the selective use of binocular stereo is of significant utility to the system.

The detection of wires and other small obstacles present a serious problem to passive techniques because of the increased resolution required to detect such obstacles at a range sufficient for obstacle avoidance. A tradeoff must be made between the FOV and the resolution of the sensor(s). Since the system's FOV must be large enough such that the vehicle has sufficient (previously scanned) directions in which to steer when obstacles are detected, the FOV of the passive sensors can not be reduced, hence a laser range scanner and an additional passive sensor with a narrow FOV are added to the system. The use of a simple (e.g., circular scanning) laser range sensor whose scan pattern is centered around the FOE, is employed for the purpose of detecting only those small obstacles that lie in the direction of travel.

An illustration of the overlapping fields of view of the three types of sensing -- optical flow, binocular stereo, and laser sensor -- is provided in Figure 2. The laser sensor provides the high resolution which is not possible with a passive sensor. On the other hand, the narrow FOV passive (multipurpose) sensor reduces the density of the laser scan. The limited FOV of the laser beam sacrifices little covertness, and the simplicity of its scanning pattern keeps acquisition time short and hardware complexity low. The gimballed laser scanner can also be used to quickly investigate avenues of safe passage when obstacles have been encountered which block the current path.

Once the range samples are obtained from the various sensors, the next step involves obstacle detection. This requires that the computed range map for the scene be sufficiently dense (so as to extract the range map discontinuities that may correspond to obstacle boundaries) or a model for the scene (segmentation of the sensed image into different types of terrain features) be available. Context-dependent image characterization, also called scene analysis, is applied to each frame resulting in a model of the scene which aids in the identification of safe paths and allows acquisition of dense range maps.

4.2 Optical Flow-Based Obstacle Detection

To describe the details of the optical flow-based obstacle detection algorithm, consider a given *pair* of image frames, A and B, along with their associated inertial data. Then, the algorithm to estimate range values to discrete 3-D points consists of the following steps: (1) Input images are segmented into regions corresponding to different scene entities, e.g., sky, road, tree, bush; (2) Interest points are extracted from each of the input frames; (3) Location of the FOE (in both frames) is computed; (4) FOE and the interest points in frame B are projected onto an image plane that is parallel to the image plane that captured frame A (*derotation* of frame B); (5) Interest points in frame B are matched to those of frame A based upon four criteria using various optical flow and rotorcraft motion constraints; (6) Range is computed to each interest point in frame B that has a match in frame A; and (7) Range estimates are improved by tracking each interest point over multiple frames. A dense range map can be created using context-dependent scene analysis and interpolating between the computed range values. These steps of the algorithm are elaborated upon in the following discussions.

Input Data Acquisition -- The input to the obstacle detection algorithm is a sequence of digitized video or FLIR frames that are accompanied by inertial data consisting of rotational and translational velocities. The inertial data together with the information about the temporal sampling interval between frames, are used to compute the distance vector, $\vec{d}$, between each pair of frames and the roll, pitch and yaw angles, (ϕ,θ,ψ), of each frame. Both $\vec{d}$ and (ϕ,θ,ψ) are crucial to the success of the algorithm.

Image Segmentation -- The features within the imagery (TV or FLIR) that are most prominent and distinguished, correspond to the 3-D points to which range measurements will be made. Unfortunately, not all regions within a scene can contain reliable interest points (e.g., sky or water bodies do not offer good interest points). The incorporation of scene segmentation results in relatively more uniform distribution of the interest points for a given scene.

Interest Point Selection -- We compute a set of distinguishable points by passing an operator, I, which is a combination of the Hessian and Laplacian operators[9] over each input frame. The operator, I, takes the form

$$I(g) = g_{xx}g_{yy} - g_{xy}^2 - k(g_{xx} + g_{yy})^2 ,$$

where g is the local gray level function, and g_{xx} and g_{yy} are the local second derivatives (computed using 3 × 3 kernels) in the x- and y-directions, respectively. In computing $I(g)$ for a particular image, the image is first smoothed by convolution with a small Gaussian kernel.

The zero-crossings of $I(g)$ are selected as interest points. Our implementation of the I operator ranks the detected interest points by the magnitude of their corresponding local maxima or *interestingness*. The number of interest points reported within a segmented image region is proportional to its size; the reported points are those that have the highest interestingness values.

Interest Point Matching -- Matching of interest points is the simplest if two input images differ by a pure translation between their coordinate frames, i.e., image plane B is parallel to image plane A. To make the image planes parallel, derotation is performed for each vector, (F, y_i, z_i),† that corresponds to each of the interest points in frame B.

The matching of interest points is performed in two passes. The goal of the first pass is to identify and store the top three candidate matches for each interest point, (F, y_{B_j}, z_{B_j}), in frame B that have the smallest distance measures of all possible matches. The goal of the second pass of the matching process is to take the matches provided by the first pass and to generate a one-to-one mapping between the interest points in frames A and B.

Range Estimation -- Given a pair of interest point matches between two successive image frames and the translational velocity between frames, the range, R, to the corresponding to world point relative to the lens center of frame A is given by

$$R = \Delta Z \frac{x' - x_f}{x' - x} \frac{1}{\cos\alpha_A} ,$$

where x_f = the distance between the FOE and the center of the image plane, x = the distance between the pixel in frame A and the center of the image plane, x' = the distance between the pixel in frame B and the center of the image plane, $\Delta Z = |\vec{v}|\Delta t \cos\alpha_F$ = the distance traversed in one frame time, Δt, as measured along the axis of the line of sight, α_F = the angle between the velocity vector and the line of sight, and α_A = the angle between the vector pointing to the world object and the line of sight. The accuracy of the range measurements is very sensitive to the accuracy of the interest extraction process, the matching process, and the accuracy of the INS data.

Matching And Range Confidence Factors -- We further improve range computations (based upon three or more sequential frames) by predicting and smoothing the range to each interest point that can be tracked through multiple frames. The procedure for prediction and smoothing of range using multiple frames is to compute, for all interest points in a pair of images, the matching confidence, confidence in range, and predicted ranges. Once the confidences and predicted range are computed, thresholds are applied and a smoothed range is computed.

5 EXPERIMENTAL RESULTS

Our inertial navigation sensor integrated optical flow algorithm has been applied to real data (imagery and INS information) obtained from a moving vehicle to generate range samples. In this section, we present the results of applying the algorithm to a five frame sequence of outdoor imagery collected along with INS data generated by a Honeywell HG1050.

The first pair of images is shown in Figures 3(b) and 3(c). The field of view of the camera used to collect these images is 32.6° x 22.1° and the focal length = 15.1 mm. The elapsed time between each pair of frames for this experiment was 0.3 seconds. Table 1 indicates the roll, pitch, yaw, and velocity of the camera associated with the sequence of outdoor frames that were used. The velocity and attitude measurements are made in the coordinate frame of the INS.

The results of processing a pair of the frame sequence are displayed in Figure 3. The image in Figure 4 is the cumulative result of processing the 5 frame sequence. In Figure 5 are shown the locations of the objects for which ground truth exists. Table 2 has the comparison of ground truth range values and the range values generated through motion analysis for 4 pairs of imagery. Note that some motion analysis range values are missing because no interest points could be extracted for these ground truth-ed objects.

6 CONCLUSIONS

This paper has presented the ODIN (Obstacle Detection Using Inertial Navigation) obstacle detection system. The objective of our obstacle detection approach has been to develop automated techniques that are preferably passive and reliable, to validate such

† Denotes a pixel in the 3-D coordinate frame $x-y-z$, where the image plane is located at $x = F$ and the z-axis points downwards.

developed techniques for reliability and graceful degradation, and to ensure their implementability in practical rotorcrafts of the present as well as of the future.

In this paper, we have analyzed the requirements of an obstacle detection system for rotorcraft in low-altitude NOE flight based on various rotorcraft motion constraints. We have concluded that an automated obstacle detection system for the rotorcraft scenario should include both passive and active sensors to be effective. Consequently, we have introduced a maximally passive system for obstacle detection which involves the use of passive sensors (TV, FLIR) as well as the selective use of an active (laser) sensor. The passive component is concerned with estimating range using optical flow-based motion analysis and binocular stereo. In this paper, we have reported the implementation of the optical flow-based motion analysis over multiple frames that is combined with inertial navigation system (INS) information to compute the range to world points that lie within the field of view of the sensors. The INS integrated motion and scene analysis leads to a robust passive ranging technique useful for obstacle detection and avoidance for land and air vehicle navigation. Our ongoing efforts are to complete the implementation of the remaining subsystems of the ODIN system.

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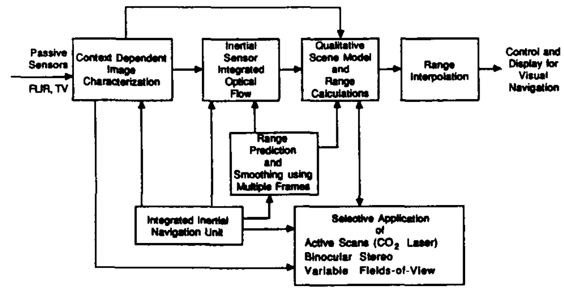

Figure 1: The schematic diagram of the ODIN system.

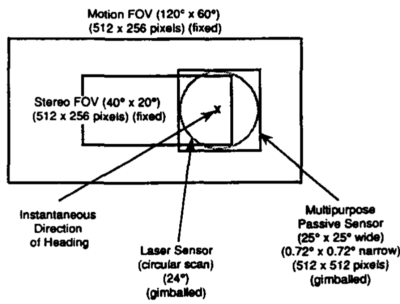

Figure 2: Overlapping fields-of-view for the ODIN system.

(a)

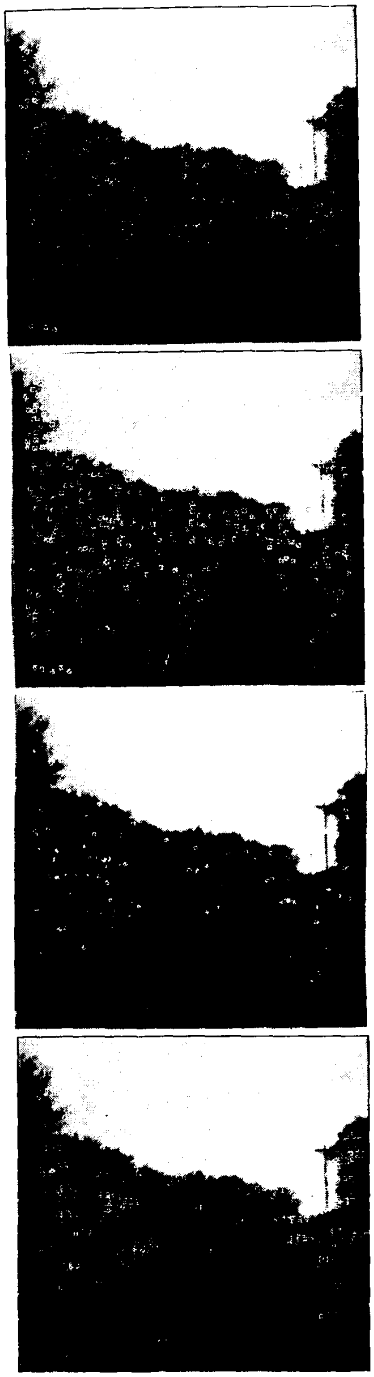

Figure 3: The results of processing one pair of the outdoor imagery: (a) the segmentation of both frames, (b) the interest points in the 1st frame, (c)the interest points in the 2nd frame, (d) the set of matched points, (e) the range to the matched points.

Figure 4: The cumulative result of processing five frames of outdoor imagery. Every interest point which was matched and assigned a range is superimposed here on the first frame of the sequence.

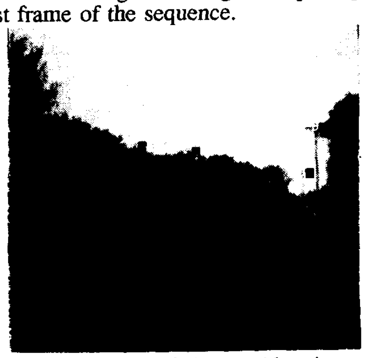

Figure 5: The locations of the world points which had associated ground truth information.

Table 1: The actual attitude and velocity measurements made simultaneously with the acquisition of the outdoor imagery. These measurements are in the coordinate frame of the INS. The vehicle was moving roughly E-NE.

Frame	Attitude (radians)			Velocity (ft/s)		
	roll	pitch	yaw	v_{north}	v_{east}	v_{down}
A	3.49e-02	2.72e-02	1.33	2.24	8.36	-0.149
B	2.99e-02	2.75e-02	1.328	2.30	8.32	-0.150
C	2.61e-02	2.90e-02	1.327	2.23	8.23	-0.150
D	2.42e-02	3.01e-02	1.326	2.19	8.23	-0.120
E	2.53e-02	2.99e-02	1.325	2.01	8.23	-0.133

Table 2: A comparison of ground truth and motion analysis range values for the outdoor imagery. The columns labeled *Actual* contain the ground truth values and the columns labeled *ODIN* contain the motion analysis generated range.

Ground Truth Location	A-B Range (ft)		B-C Range (ft)		C-D Range (ft)		D-E Range (ft)	
	Actual	ODIN	Actual	ODIN	Actual	ODIN	Actual	ODIN
A. 1st Telephone pole	231	185.	228	276.	226	245	223	202
B. 2nd Telephone pole	486	367	483	366	480	427	478	–
C. Treeline #1	502	–	499	–	497	430	494	–
D. Treeline #2	665	300	663	298	660	–	658	446
E. Treeline #4	388	–	385	–	383	255	380	–
F. Pole by gate	214	298	212	–	209	236	206	175
G. Red light post (closest to road)	153	186	150	322	148	–	145	165
H. Red light post (closest to gate)	156	167	153	343	151	114	148	157
I. Fence Post by gate (West end, closest)	169	160	167	172	164	–	162	161
J. Fence Post by gate (West end, farthest)	156	209	153	–	151	165	148	153