THE APPLICATION OF MULTI SENSOR DATA FUSION TECHNIQUES TO ROTORCRAFT OBSTACLE AVOIDANCE SYSTEMS

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Abstract

This paper addresses the application of multi sensor data fusion techniques to the problem of estimating the tracks of static and dynamic obstacles in the vicinity of a helicopter operating in a reduced visual cue environment. The work was undertaken by GKN Westland Helicopters Ltd (GKN WHL) in collaboration with Southampton University under a UK Department of Trade and Industry (DTI) and Ministry of Defence LINK research programme. The project, known as Helios, resulted in sensor models, data fusion and flightpath guidance algorithms developed by Southampton University being installed on a fixed base helicopter simulator at GKN WHL. Simulations were conducted to assess the performance, accuracy, and robustness of the system. Piloted demonstration flights also assessed a novel symbology suite designed to increase pilot's situational awareness, and facilitate obstacle avoidance manoeuvres.

Introduction

The majority of helicopters operate under visual flight rules (VFR) and use the lowest portion of the airspace, with visual reference to the surface Typically helicopters operate at lower altitudes for a greater proportion of time than fixed wing aircraft, making them vulnerable to obstacles. These include power cables and pylons, communications masts, other aircraft, terrain, and man made features such as buildings, bridges, etc. Military operations are particularly hazardous, but problems exist in demanding civil roles such as emergency medical services (EMS) or offshore platform support, especially on approach and landing in poor visibility to non-prepared landing sites. Clearly the problem is more acute at night when there is almost total dependence on sensors for obstacle cueing. In addition to improved all weather landing capability a system is required to provide autonomous obstacle protection.

Sensor systems are available which are capable of detecting obstacles. Active obstacle detection sensors include forward looking millimetric wave, and laser radar systems, thermal imagers and secondary surveillance radar systems such as TCAS. In addition, terrain database technology can augment active obstacle detection by providing passive ground collision protection.

However, each sensor only provides a limited obstacle coverage. Sensor performance can also be degraded by atmospheric conditions. To provide reliable, full coverage obstacle detection in all weather, a suite of sensors is required.

Helicopter flight at low level is already a high workload task. The crew are required to assimilate and fuse data from a wide range of sources to create a mental model of the state of the world. They are frequently required to cope with uncertainty and time pressure due to conflicting, simultaneous, real time tasks. Assimilating further information from multiple obstacle sensors will increase the workload of an already demanding task to an unacceptable level, especially if the sensor data is conflicting. To reduce the workload associated with a multi-sensor obstacle avoidance system (OAS), there is a real need to find ways of assisting the crew in this task. The system must fuse and correlate the data prior to presenting it to the crew as a single coherent picture of the obstacle situation.

The object of this project was to examine the applicability of real time data fusion techniques to an autonomous obstacle protection system, capable of operating over the complete flight envelope in all weather conditions. The sensor suite was chosen to provide a system capable of detecting mobile obstacles, terrain and un-mapped features, with a design goal of providing 30secs warning of all obstacles.

An important aspect of the obstacle avoidance system is knowing exactly where the aircraft is in relation to the obstacles. Position accuracy can be improved using data fusion techniques to combine the outputs of existing aircraft sensors such as Global Positioning Systems (GPS), inertial navigation systems (INS), rad alt and air data systems (ADS). The system was designed to maximise the use of existing onboard sensor data to minimise its cost and weight.

To demonstrate the functionality of the system it was

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implemented on a fixed base helicopter simulator at GKN WHL. This included modelling the sensors, development of the localisation and obstacle avoidance algorithms, and definition of the human machine interface (HMI). The design of the system, the simulator integration, evaluation scenario and simulation results are presented below.

Sensor Fusion Techniques

The objective of multi-sensor data fusion (MSDF) is to combine data from different sensors into a single set of meaningful information that is of greater benefit than the sum of its contributing parts. To facilitate this fusion, a coherent framework (modelling) is required to describe the phenomena involved in the process. The phenomena can be separated into two groups; one relating to the object kinematics, i.e., process models, and the other relating to sensor reports, i.e. sensor models. The formation of a kinematic model requires the specification of the variables, or states of the object that need to be estimated, and the equations, or dynamic model, that relates the object state from one instant in time to the next. Modelling the object states requires the specification of a number of state variables and a reference coordinate frame for the object variables. The specification of the object's dynamic model involves modelling the object's capability to execute manoeuvres.

The formulation of a sensor model comprises the partitioning of the measurements generated by the sensor (a single *scan* of measurements producing a *report*), derivation of the relationship between sensor measurements in a report and the object's state, establishing a model for the measurement error in each report and finally allowing for the fact that objects of interest may not be detected by every scan.

From this, data association and the fusing of data from multiple sensor systems into object tracks can occur. Data association is the correlation of reports from multiple sensors and the predicted locations of already detected obstacles from previous scans, with each report being assigned one of the following hypotheses:

- The report is a member of a new detection set.
- The report is a member of an existing set, identifying the object as a previously detected object.
- The report is a false alarm.

At the end of each scan, state estimation (object tracking) is performed, from the sets of new and existing sensor and object reports. A dynamic model of behaviour is assumed and the parameters (eg. position, velocity) are estimated based on sensor measurements. These estimates are then used to predict the location of objects at the point in which the sensors will locate them in the next scan. Predictions are fed back for association on subsequent scans and the output of this stage is the estimate of state of each object.

The static association and dynamic tracking processes require estimators that convert observation data into accurate estimates of object state.

There are a number of methodologies applicable to the MSDF processes, but they generally fall into three broad categories of formalisms; statistical methods, neural networks and fuzzy logic. Bayesian and Dempster-Shafer methods are the most commonly used statistical formalisms for MSDF. Currently, the Kalman Filter (KF), a Bayesian statistical estimator, and its various adaptations, are the state estimators most commonly used for dynamic tracking. The other formalisms applied to MSDF, neural networks and fuzzy logic, have shown promise in tackling non-linear problems and offer alternate representations for uncertainty. Neuro-fuzzy estimators developed for single sensor state estimation by Southampton University indicate the possibility of state estimators superior to the KF for non-linear state estimation problems.

Kalman Filters

The KF is the general solution to the recursive, minimised mean square estimation problem within the class of linear estimators, estimating the unknown states of a dynamic process from noisy data sampled at discrete real-time intervals. Some assumptions are made in the formulation of the KF equations which may mean that their performance is sub-optimal. The most important of these is the fact that the KF assumes that the process estimated is linear. The Extended Kalman Filter (EKF), a variation of the KF, attempts to deal with this restriction and is specifically designed to be applied to non-linear processes. However, this method is only a linear approximation based on the first terms of the Taylor series expansion of a non-linear process. This limitation of the EKF has not restricted its widespread use by industry. Applications such as video and laser tracking systems, satellite navigation, ballistic missile trajectory estimation, radar and fire control are all examples where the use of the EKF is commonplace, forming the backbone of most current tracking algorithms. The KF requires a knowledge of the noise of the process being observed and of the measurement noise in order to provide the solution that minimises the mean square error between the true state and the estimate of state.

Two other variations on the KF theme are also worthy of mention. They are the Decentralised Kalman Filter (DKF) and Adaptive Kalman Filter (AKF). The DKF is an adaptation of the ordinary KF to work in a decentralised architecture, i.e. an architecture which ensures that each sensor node arrives at the same estimates as those which would have been obtained had an ordinary KF been used with a hierarchical centralised architecture. Each individual node makes its own predictions about what will be observed, producing a partial estimate of the environment. An additional stage is then evoked in which these partial estimates are broadcast to other nodes where they are assimilated to provide the full environment estimate. This has obvious advantages in that the failure of any one node will not result in a whole system failure. The AKF relies on systematic methods of tuning the process noise to achieve some desirable performance criteria.

Neural Networks

Artificial neural network models are hardware or software systems that seek to emulate the workings of the biological nervous system. A neural network consists of layers of processing elements or nodes that may be interconnected in a variety of different ways, performing a non-linear transformation on input vectors. Neural networks must be *trained* to perform correct classifications by systematically adapting the weights, or gains, at each interconnecting node. This is typically performed using samples or training sets in which the object identities are known. One of the main drawbacks to neural networks from an MSDF viewpoint is that trained networks are, in general, not transparent, i.e. it is extremely difficult to explain how they arrive at particular categorisations. The relationship between input and output is generally highly complex owing to the widespread distribution of contributing information in the network (implicit in the adjusted weights). However, there is a class of neural network that is more transparent than conventional networks, called Associative Memory Networks (AMN). AMNs store information locally, distinguishing them from other neural networks. The internal representation used in the AMN makes them more transparent than conventional networks which is especially true for fuzzy and B-spline algorithms which can be represented as a set of imprecise production rules. The link between fuzzy networks (see next section) and neural networks is important, and AMNs provide a common framework with which to study both areas. This is useful because it allows new learning rules to be developed for training fuzzy rules, and allows AMNs to be interpreted as a set of fuzzy rules which can aid the initialisation and verification phases in a network design and test cycle.

Fuzzy Logic

The basic philosophy of fuzzy set theory is that people frequently deal with concepts that are imprecise because they cannot be adequately defined. Terms such as *tall*, *short*, *attractive* or *ugly* are imprecise not because the human thought processes utilising them does not understand them, but because the terms refer to attributes which are inherently imprecise. Each element in a fuzzy set has a value which indicates the degree to which it belongs to the set.

The real value of fuzzy set theory to MSDF is in its extension to fuzzy logic. Fuzzy logic deals with approximate modes of reasoning. Classical logic uses truth tables and manipulation rules to follow a chain of reasoning to determine the truth (or falseness) of a proposition. By contrast, in fuzzy logic a proposition has a membership value representing the membership of the proposition to the truth value set. In a sense, a fuzzy truth table may be viewed as an imprecise characterisation of a numerical truth value. Fuzzy logic is well defined, with a means of representing fuzzy propositions, combination rules and inference.

The value of fuzzy set theory and logic for data fusion is still being researched, and although fuzzy systems have been considered extensively for modelling, little attention has been paid to the subject of estimation. In this programme this challenge was confronted by the University of Southampton by a combination of AMNs and fuzzy logic. Unknown functions which describe estimators could be modelled as fuzzy rule sets, the rules being identified off-line using simulated process data and measurements. Since many fuzzy models use least mean square type adaption laws, the resulting estimator would produce near optimal estimates for the training data set. The selection of a representative training set and the fuzzy model property of generalisation would then ensure that the system produced good estimates in a real situation.

Neuro-fuzzy Networks

Neuro-fuzzy estimators have fuzzy models which describe the various relationships between inputs, states and observations, and are produced using fuzzy neural networks based on B-spline AMNs. They provide guaranteed learning convergence and temporal stability, and as such are an efficient way of forming the required fuzzy models. The real-time learning capability also ensures that the estimators can be adapted on-line to better model the process being observed.

Good estimates of an obstacle's states are not sufficient in themselves for the purpose of helicopter obstacle avoidance. An indication of the possible variance of these estimates is also required in order for the helicopter to confidently plot a course through the obstacle field. Fuzzy logic provides a means of indicating the possible variance of the estimate. In the standard KF approach, the possible variance of the estimates is provided by the covariance matrix, whose diagonal elements represent the variance of an assumed Gaussian distribution. The distribution of fuzzy sets, however, is not confined to Gaussian distributions, and hence offers greater potential for variance representation. Also, the KF assumes that process and measurement noise are white Gaussian with zero mean and uncorrelated. The distribution of fuzzy input sets does not have to be restricted in this fashion.

System Description

Selection of Sensor Suite

In selecting a sensor suite, the main aim was to provide a system capable of avoiding obstacles in a wide range of hazardous conditions which would be robust in the face of individual sensor failure and involve minimum alteration to the aircraft. The equipment fitted should be currently available and its size, volume and weight should be broadly applicable to a mid-sized, twin engined helicopter. In light of these considerations, the following sensors were chosen:

- Inertial Navigation System (INS).
- Radar Altimeter (RadAlt).
- Air Data System (ADS).
- Global Positioning System (GPS).
- Traffic Alert and Collision Avoidance System (TCAS).
- Microwave radar.
- Forward looking millimetric wave radar.
- Terrain database.

The INS, RadAlt, ADS and GPS are likely to be installed on the majority of rotorcraft currently entering service, and hence are useful information sources which are already in position. GPS has recently become a popular and inexpensive method of determining own aircraft position, with accuracies down to one hundred meters, or the order of tens of meters when using differential GPS. The first additional sensor, TCAS, is in widespread use in the USA, providing positional information about other aircraft in the vicinity equipped with a secondary surveillance transponder. The two radars assist in detection of dynamic obstacles and obstacles not present in the terrain database. The microwave radar, scanning 360 degrees in azimuth, ±20 degrees elevation and having a range of 5 kilometres, detects other relatively large obstacles (eg. other aircraft) in the vicinity. The forward looking millimetric wave radar, scans 20 degrees in azimuth, ±10 degrees in elevation and has an effective range of 2 kilometres. The resolution is quite low, only providing 34 by 17 pixels, but this is sufficient for small obstacles such as birds and power cables in the path of the helicopter.

OAS Architecture

There are three stages to the OAS; navigation sensor data fusion for the purpose of localisation, object detection and tracking data fusion, and route planning. The two sensor data fusion stages are shown in Figure 1. The diagram shows the sensor inputs used for each of the two stages. In the localisation stage, *External Sources* could consist of data linked air traffic control commands, or differential GPS aiding. The different navigation sensor data are fused together to produce 'best' navigation data. These estimates would be part of the *External Sources* input into the second stage, object tracking.

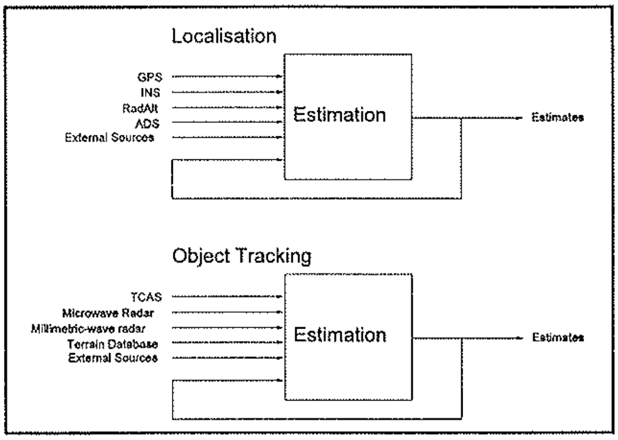

Figure 1 - Basic estimator structures

The third stage, route planning, uses an artificial potential field approach to obstacle avoidance, which is a reactive, real-time solution. The OAS has knowledge of the flight plan. Points along the desired path are assigned attractive forces and obstacles in the environment are assigned repulsive forces. The interaction between the artificial potential fields causes a net force which guides the helicopter along an obstacle free path to the next point on the flight plan. All obstacles produce repulsive potential fields which are enlarged by the uncertainty in their detected position, and which increase in strength as they are approached. This strategy uses three dimensions in plotting a safe route through the obstacle field.

Consider the two dimensional obstacle avoidance situation shown in Figure 2. The obstacle is constrained to move only in the x/y plane. The surface above this plane represents the strength of the artificial potential field at each point in the plane. Imagine that the helicopter is a negatively charged particle trying to reach the positively charged goal position. If there were no obstacles in the way, it would be a simple matter of moving in a straight line between start and goal. However, when there are obstacles present, their negative charge repels the helicopter. If you consider a ball bearing on the field strength surface above the plane, it will roll down this surface in the opposite direction of the gradient of the field at that particular point. Projecting this motion onto the plane results in the indicated non-linear path avoiding the obstacles. The important point to note is that the ball bearing always travels in a direction which is opposite to the gradient of the field at that particular point.

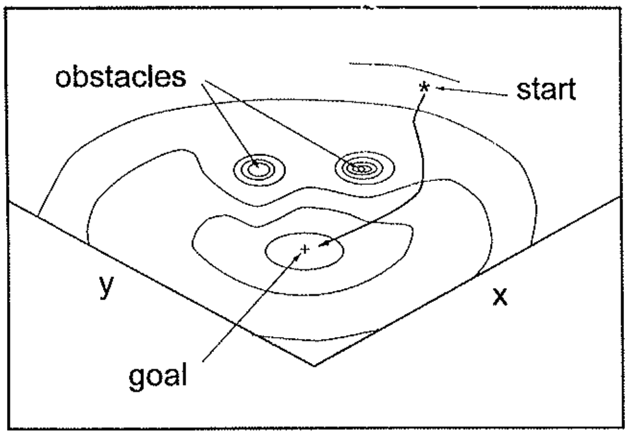

Figure 2 - Artificial potential fields

Therefore, to use the artificial potential field approach for obstacle avoidance, the gradient must be calculated of the field at that particular moment in time. This calculation can be done in real time, and results in a proposed flight path that is predicted 50 seconds ahead of the aircraft.

OAS Performance

This section presents some performance results from the data fusion and obstacle avoidance subsystems. These were implemented on a standalone workstation prior to integration with the simulator.

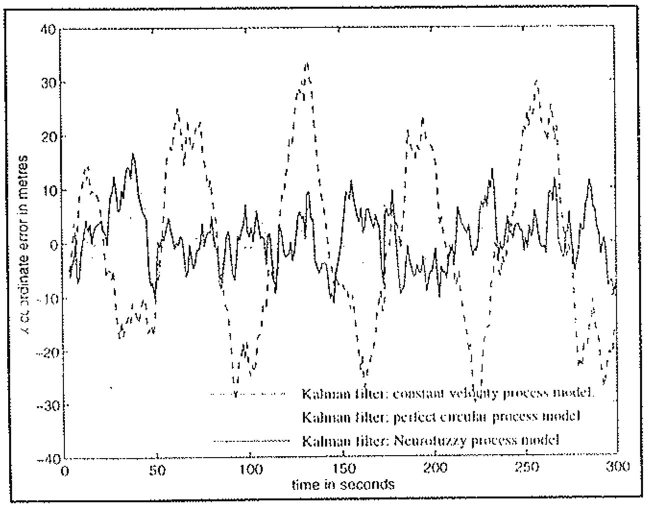

Figure 3 - Comparison of localisation errors for circular flight

Figure 3 compares localisation errors in the x coordinate while the helicopter flies in a circle of radius 500m (at a constant height) and at a speed of 50m/s.

Table 1 compares the mean and standard deviation of the output errors of each of these filters. It can be seen that a Kalman filter using a constant velocity process model is unable to deal adequately with this manoeuvre by the helicopter. This is rectified by employing a circular process model. There is very little difference between the output produced by the filter which has a perfect model of the circular manoeuvre and the one which uses a neuro-fuzzy network trained on observations of circular manoeuvres. Neuro-fuzzy networks may be trained to model any possible manoeuvre purely from observational data.

Model	Mean	Standard Deviation
Constant velocity	0.871	16.234
Circular process	0.062	3.935
B-spline process	0.558	5.483

Table 1 - Comparison of filter errors (in metres) for circular flight

In the following results from the evaluation of the obstacle avoidance subsystem, the helicopter is flying at a constant speed of 30 metres per second. All figures are two dimensional projections of the path of the helicopter.

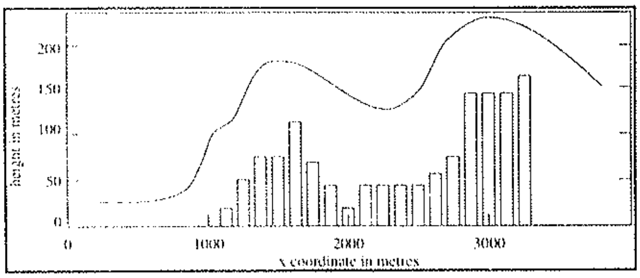

Figure 4 - Terrain avoidance using millimetric wave radar

In Figure 4 the terrain database is not providing the helicopter with any information about the terrain. Instead, all terrain information is coming from the millimetric wave radar image. In this case the helicopter gets repulsed by all the positions indicated by the pixels in the millimetric wave radar image. The path produced using repulsion from the millimetric wave radar will generally produce a path which is further from the terrain than one which used a terrain database due to the increased uncertainty associated with the radar returns. Any pixel in the millimetric wave radar image might in fact be a return from a dynamic obstacle.

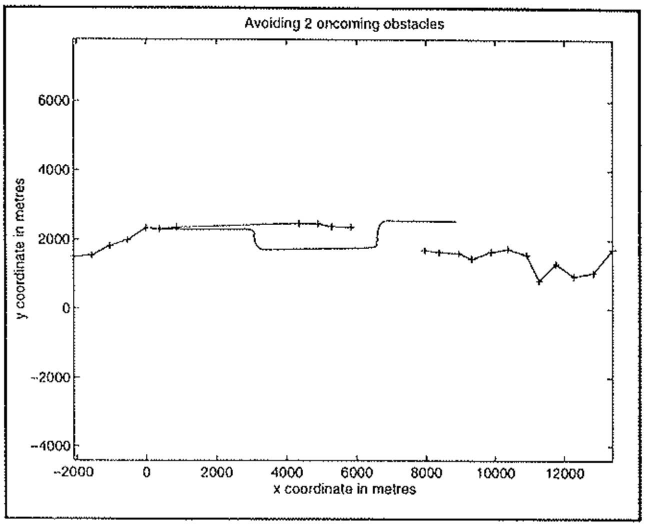

Figure 5 - Avoiding two on-coming obstacles

Figure 5 illustrates the smooth path derived by the obstacle avoidance system to avoid two on-coming obstacles. In this example the obstacles are travelling at speeds of 30 metres per second in the opposite direction to the helicopter's path. The obstacles are being tracked using a microwave radar.

Simulator Integration

The system described above was integrated into the the Advanced Engineering Simulation Facility (AESiF) at GKN Westland Helicopters. This is a fixed base helicopter simulator consisting of a side-by-side cockpit, a fully configurable glass instrument panel and computer generated outside world visuals projected onto a curved screen covering 180 degrees by 45 degrees. The computing power comes from a suite of Silicon Graphics workstations, the main driver of which is an Onyx Reality Engine 2. This runs the three channel outside world graphics, positioning the aircraft in the world in response to control inputs fed in by the pilot and interpreted by the flight dynamics model, executing on the 320VGX PowerVision. A number of other machines are used to drive HDDs, and to run peripheral systems, such as, in this case, the sensor models, data fusion and obstacle avoidance systems.

There were extensive inter-machine communications required in order to implement the Helios system.

These systems included:

- Outside world graphics
- HUD
- Helicopter flight model (Conceptual rate command, attitude hold, control law based around a Mk7 Lynx, with maximum all-up weight)
- Forward looking millimetric wave radar (MMW)
- Other sensor models
- Sensor data fusion process
- Obstacle avoidance process
- Primary flight display
- OAS HDD
- Data logging (for post-run analysis)

The workstation based architecture is shown in Figure 6, which also details the type of workstation utilised for each function. Inter-machine communications were performed on an Ethernet (10BaseT) data bus. The data flow *helo state* contains helicopter x, y, z position, pitch, roll yaw attitudes and engine torques, rotor speed, climb rate, etc., and is used for, among other things, aircraft positioning in the outside world and as inputs to the various sensor models. The flow *Other Player data* contains state information of dynamic obstacles in the simulation, and *Image data* is a snapshot frame of the current MMW radar scan.

OAS HMI Philosophy

The key to successful obstacle avoidance is maintaining the pilot's situational awareness. This is best maintained by keeping the pilot in the loop. It is feasible to couple the OAS to the automatic flight control system providing automatic obstacle avoidance. However, this raises interesting questions about the role of the pilot in the system. Automating the system changes the pilot's role from an active participant to that of a monitor. Humans are notoriously poor monitors. The pilot's awareness of what is going on around him would be reduced, and should the automated system fail, the pilot may be unfamiliar with the situation and unable to re-orientate in time to recover.

The pilot brings considerable knowledge to the obstacle avoidance problem and has the best picture of the overall goals of the mission. The pilot may be aware of information not available to an automatic system and his/her strength is the ability to solve novel or unpredicted problems. For these reasons it was decided that the OAS should be configured as an advisory system, and should not be coupled to the

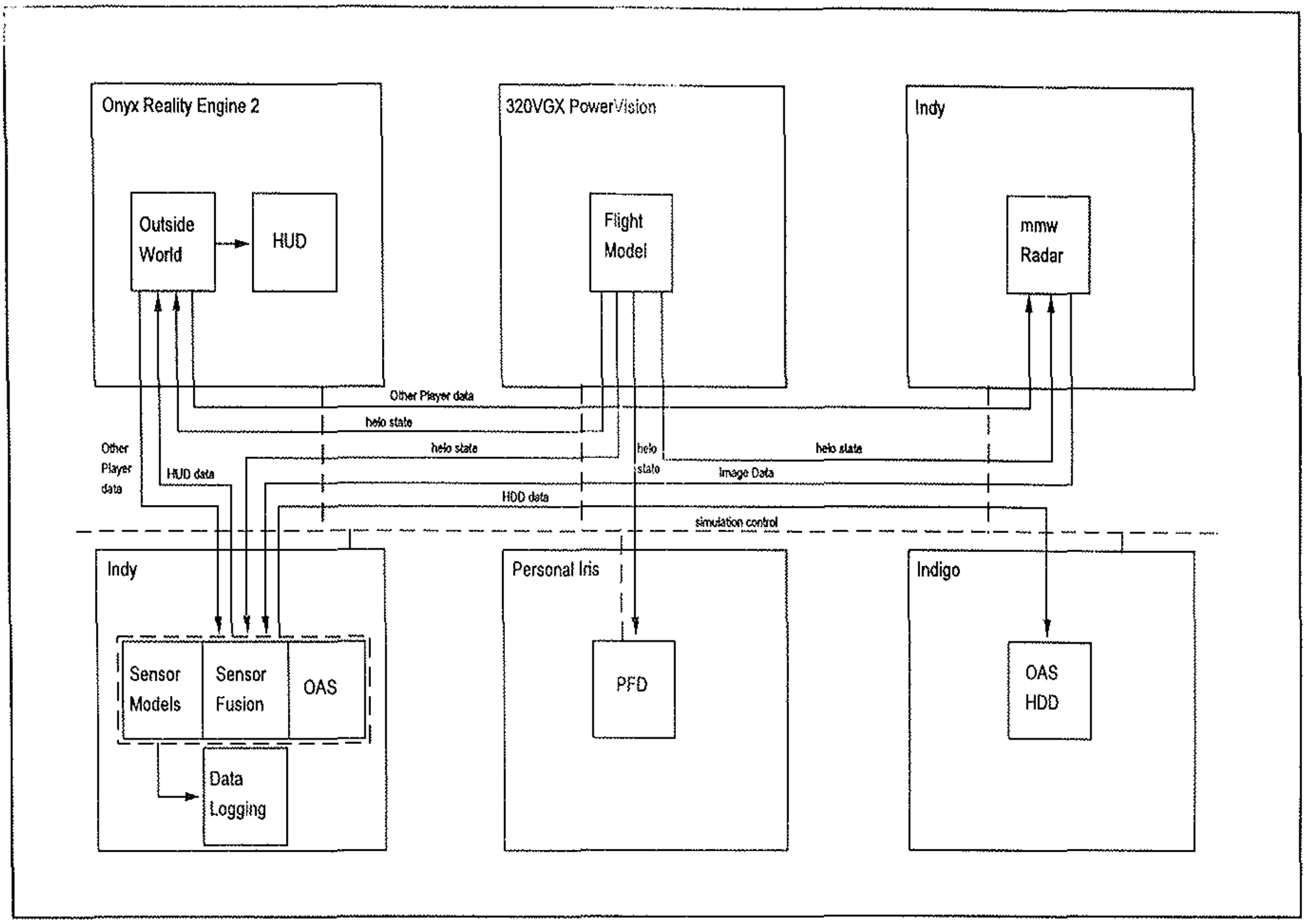

Figure 6 - AESiF architecture for Helios programme

autopilot. The system provides steering commands to the pilot which he/she can choose to follow or ignore.

Head Up Display (HUD)

Helicopter flight, particularly at low level is primarily a visual flying task. Therefore the primary interface for the OAS should be head up, ideally helmet mounted, in order to maintain eyes out flight at critical times of the flight. It should provide primary flight information allowing heads up flight in poor visibility. It should also provide world referenced obstacle cues to augment the pilot's view of the world under poor visibility conditions. Care must be taken to not over burden the pilot with head up symbology and block his/her view of the outside world. An optional flight director mode provides flight path guidance when required by the pilot and reduces clutter when not required.

Lack of availability of a helmet mounted display confined the simulator evaluation to the use of HUD symbology. The HUD was simulated as part of the outside world scene overlaying the pilot's view along the aircraft centreline. The HUD provided primary flight parameters and obstacle avoidance symbology. The symbology was adapted from an existing format and provided the pilot with attitude information (Pitch, roll, yaw), sideslip, heading, airspeed, altitude, rate of climb, engine torque, and rotor speed. In addition the HUD was adapted to indicate the position of dynamic obstacles in the world. This was achieved using circles which overlaid the pilot's view of the obstacle. The diameter of the circles was inversely proportional to the range of the obstacle from the host aircraft. See Figure 7.

A pilot selectable obstacle avoidance mode was also added to the HUD. Mode selections were made via a cyclic mounted toggle switch. This mode provided the pilot with flight path guidance symbology. Figure 8 illustrates the "tunnel in the sky" concept used to convey flight path guidance. The squares represent an instantaneous snapshot of the suggested flight path over the next 50 seconds as calculated by the obstacle avoidance algorithm. Each square represents a suggested waypoint with a lateral deviation of ±10m at 10 sec intervals in the future. The pathway is dynamic and continually updates in real time. It provides an obstacle-free pathway to the next point on the flight plan. Each square is roll-stabilised to provide roll attitude references. Speed cues are provided by the size of the squares; as the aircraft slows down the squares get larger, and vice versa.

Preliminary work led to the addition of a diamond shaped aircraft velocity vector (VV) symbol and a

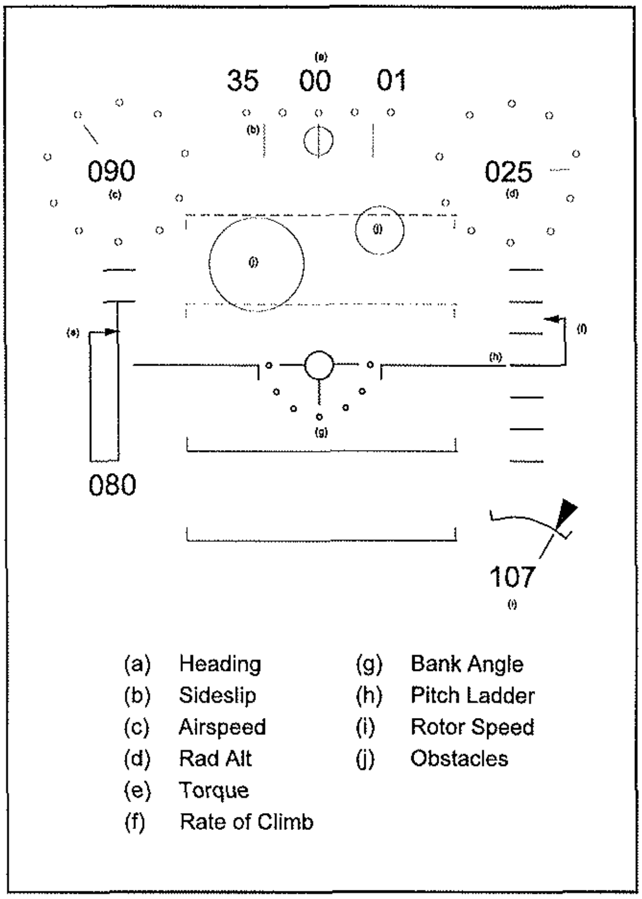

Figure 7 - HUD Symbology

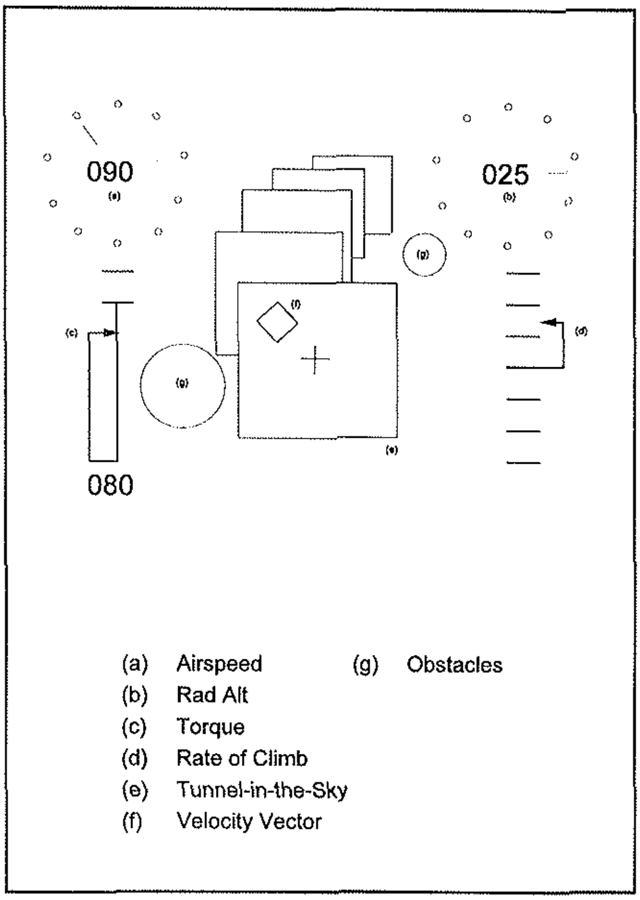

Figure 8 - HUD obstacle avoidance mode

cross-hair target at the centre of the first square.

The pilot's task was to control the aircraft velocity vector, aiming to keep it within the confines of the first square. Centring the VV on the cross hairs allowed the pilot to follow the suggested path with pinpoint accuracy. Subsequent squares provided the pilot with an indication of the likely profile to be flown within the next 40 secs, allowing him/her to make the necessary adjustments to the aircraft flight path in advance.

If the tunnel symbols disappeared from the HUD, for example if the required turn radius to achieve the safe pathway was extremely acute, then an arrow appeared at the centre of the HUD indicating the direction in which to fly to re-acquire the tunnel. In addition the bank angle indicator from the standard HUD was displayed, to provide roll attitude information.

All symbology was shown in green. Colour-coding was not used as colour HUD technology is not yet commercially available. Flashing was used to highlight obstacles with estimated times to impact of less than 10 secs.

No visual terrain conflict warnings were provided on the HUD. The addition of a terrain lattice underlay to the HUD symbology to provide ground references in poor visibility conditions was considered, but rejected as it would clutter the display. The system accounts for terrain and unmapped obstacles in the flight path guidance calculation. In addition a dedicated audio warning of potential terrain conflicts was implemented.

Head Down Display (HDD)

In addition to the primary head-up display, the pilot requires knowledge of the obstacles outside his immediate head-up field of view to maintain total situational awareness. This can be provided by a head down plan position/situation display. Previous work has suggested an advantage for perspective based plan position formats over traditional two dimensional formats. (Ref 1). Perspective displays have been demonstrated to provide easier assimilation of the azimuth and elevation position of other aircraft relative to the host aircraft, and are less prone to error.

The head down situation display implemented here included symbology designed to indicate the location of other air traffic (obstacles) within the vicinity of the host aircraft. The display consisted of 4 concentric ellipses centred on the middle of the display. The ellipses are perspective views of imaginary concentric circles of a known size drawn around the host aircraft at the same altitude, see Figure 9. The outermost ellipse represented a range of 12 nautical miles from the host aircraft[ii]. The host aircraft is shown as a cross at the centre of the display. The cardinal points of the compass are marked on the outer range ring. The range rings rotate to reflect the host aircraft's current heading and the display was always presented "track-up".

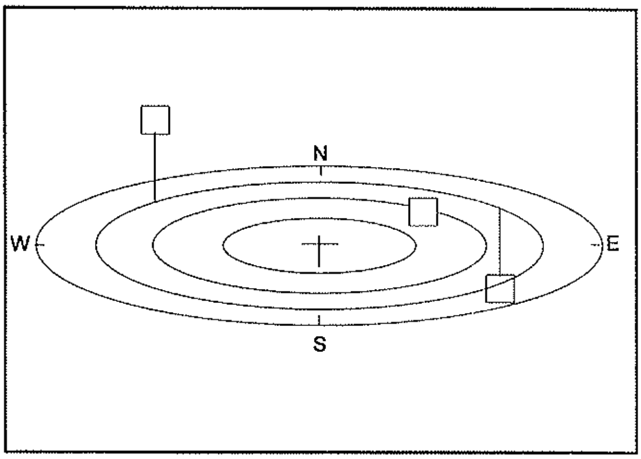

Figure 9 - Head down situation display

Other aircraft or obstacles detected by the OAS were shown as squares, each symbol having an associated relative height vector which connects it to the plane of the ellipse. The length of this line indicates the height differential between the obstacle and the host aircraft. The intersection of this vector and the plane of the ellipse indicates the bearing of the obstacle from the host. The juxtaposition of the symbol and the relative height vector indicates whether the obstacle is above or below the host. (i.e., if the symbol is at the bottom with the vector extending upwards, the obstacle is below the host, and if the symbol is at the top of the line with the vector extending downwards, the obstacle is above the host.)

Obstacles within ±500 feet vertically of the host were shown as squares with no stems. In the event of symbology conflicting for the same display area obstacles closer to the host take priority and will overlay other symbols. The closest obstacle was determined by the estimated time to impact as calculated by the system.

The system categorised each obstacle detected in terms of the threat it represents to the host aircraft. This was based on the obstacle's estimated time to impact. Three levels of threat were represented. Obstacles with a time to impact of less than 10 secs were presented in red. Those with times to impact between 10 and 19 secs were shown in amber, and those with times to impact of 20 secs and longer were shown in green.

Each red obstacle flashed at a rate of 2 Hz to alert the pilot to its presence. In addition an audio warning was also given. This could be cancelled by means of the cyclic mounted warning cancel button which inhibited the flashing and the symbol reverted to a constant red. Once acknowledged the obstacle symbol was not able to flash again without first having attained a lower threat status (amber or green).

The head down display did not display terrain data. Calculations indicated that for a helicopter travelling at an assumed max speed of 140Kts (72 m/s) the system would provide 30 secs warning of terrain which encroaches into the aircraft's flightpath at a range of 1nm. At this range the head down display would not have sufficient resolution to present meaningful terrain information and it could potentially mask the presence of other obstacles. At close range the pilot would be flying head-up using the HUD for terrain avoidance manoeuvring.

Audio Cues

Audio warning cues can be used to augment visual obstacle cues. The audio channel allows redundant warning cues which can alert the pilot independently of his/her visual attention. Advances have been made in the use of directional audio within the cockpit environment (Ref 2). This provides a natural and intuitive method of localising the position and direction of movement of obstacles. Lack of availability prevented the use of three dimensional audio cues. However, three distinctly separate, non directional audio cues were implemented.

A klaxon-like signal was used to indicate potential conflicts with dynamic obstacles with a predicted time to impact of less than 10 secs (i.e., red warnings).

A separate tone was used to indicate a predicted terrain conflict within the next 30 secs. This tone had entirely different characteristics to reduce confusion.

In addition to predictive warnings of terrain conflicts, preliminary work suggested that a reactive low height warning was also required. This was implemented as a "150 feet" voice message which was triggered as the aircraft passed below 150 feet Rad Alt.

All audio warnings could be cancelled by the warning cancel button on the cyclic.

Cockpit Switches

A mode select switch mounted on the cyclic allowed the pilot to select the information to be displayed on the HUD. This was a toggle switch permitting the pilot to change between the symbology modes shown in Figures 7 and 8.

[ii]12nm allows 30 sec warning of a fast jet travelling at mach 2.0 on a direct collision course with the host aircraft flying at 140 kts.

To allow the pilot to maintain hands-on flight without distractions during obstacle avoidance manoeuvring, a button was provided on the cyclic to allow the pilot to cancel warnings.

Simulator Demonstration

The system was subjected to a series of demonstration flights by GKN WHL test pilots in the AESiF. The objective of this exercise was to finalise the functionality of the system, optimise the symbology and provide preliminary data on the performance of the system.

Demonstration Sortie

During the evaluation the pilots flew a standard scenario from sortie to sortie to provide consistency in the results. This scenario is illustrated in Figure 10. The pilots were required to take off from an airfield at point A on the database and fly a straight line course due north over mountainous terrain to the airfield at point B. Visibility was reduced by introducing thick fog and the pilots were therefore required to follow the flight path suggested by the obstacle avoidance symbology. A hot air balloon and an airliner were simulated on direct flight paths from point B to point A, i.e., towards the host aircraft, to provide mobile obstacle threats.

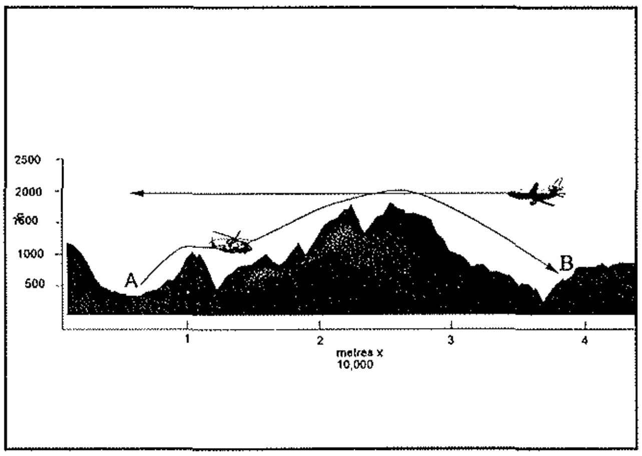

Figure 10 - Demonstration Scenario

The same terrain data base was used to create the outside world as was used by the OAS. However, the resolution of the airborne terrain database was reduced in order to model the likely discrepancies between this database and the real world. In addition the terrain database used in the outside world scene was modified at selected points to simulate unmapped terrain. This included raising the altitude of a ridge line to see if the system was able to detect this. Unmapped culture features such as communications masts and power cables were also added to the outside world data base along the expected course of the helicopter.

Simulation Results

During the demonstration flights a number of parameters were recorded for later analysis. These parameters included the estimated position of own aircraft, real position of own aircraft, estimated position of obstacles and real position of obstacles. The data collected in these trials is still being processed, however, preliminary data is available and is presented below.

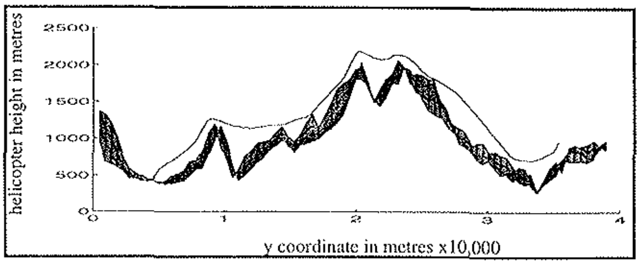

Figure 11 - Avoiding mapped terrain

Figure 11 illustrates the flight path taken by the aircraft to avoid terrain which has been mapped in the terrain database. This path is taken from a single simulation run of 15 minutes where there were no dynamic obstacles or unmapped features to avoid. This demonstrates that pilots were able to successfully complete the sortie avoiding the terrain en route, by following the flight path suggested by the system.

A number of changes to the system were implemented during the demonstration following pilot comments. These included the addition of the velocity vector (discussed above) and improvements to the attitude references in the flight path guidance symbology. Originally the tunnel was presented as a series of circles. This provided poor roll attitude cues in reduced visibility. To address this problem the circles were modified into roll stabilised squares. Pilots reported some improvement, but felt that attitude information could be improved further.

The flight control strategy used in the demonstration also contributed to poor attitude reference cues. For convenience the demonstration flights were flown using a conceptual flight control model which provided a rate command, attitude hold, control strategy. This strategy provides no constant aircraft attitude references and has been shown to result in poor performance under reduced visibility conditions.

Pilots also reported difficulty in following the flight path suggested by the system. A contributing factor to this problem was that the route planning algorithm did not account for the available aircraft performance. It initially provided waypoints at 50 metre intervals in front of the aircraft. When the aircraft was flying at high speed the suggested turns would often be too tight and the tunnel symbology would disappear from the HUD. The route planning algorithm was adapted to provide pathway points separated in time rather than distance to reduce the effects of aircraft speed.

Conclusions

The Helios programme resulted in a successful demonstration of the feasibility of a Multi Sensor Data Fusion helicopter obstacle avoidance system. It demonstrated the applicability of the neuro-fuzzy estimators and the artificial potential field theory to the non-linear problem of helicopter obstacle avoidance. The demonstration was a useful integration and optimisation exercise which resulted in a number of changes to the system and a better understanding of the issues involved in the design of an obstacle avoidance system.

The next step is to validate the results. The demonstration exercise reported on above was limited in its scope. A more rigorous examination of the system performance is required. The feasibility of the system was demonstrated using relatively crude sensor models. These must be validated prior to any further work.

The strength of the system design is that it will allow systematic variation of the performance of individual sensors. The system architecture will also allow the addition or removal of sensors permitting examination of the effects of individual sensors on overall obstacle avoidance performance. By systematic variation of sensor performance it should be possible to optimise the sensor suite, and required sensor performance for particular operational roles. For example, fusing data from several sensors may reduce the required specification and therefore cost and weight of other sensors. The system architecture also provides scope for development of a distributed, decentralised sensor system. Such a system would integrate information from sources outside the host aircraft with on board sensor data. For example air traffic control information could be input by the pilot or datalinked to the aircraft. The addition of a datalink will also permit sensor data to be shared by aircraft. Obstacle avoidance systems on light aircraft could be augmented by sensor data received from other aircraft. This may reduce the complexity of the system required by light aircraft, resulting in significant cost and weight savings.

A number of further areas for research have resulted from this programme. This includes the integration of a helmet mounted display system and a suitable symbol set as part of the HMI. The symbology used in this demonstration was crude but effective. Test pilots requested improvements to the tunnel in the sky concept. These included improved correlation of the tunnel symbology with the real world. The tunnel was not occulted by the terrain, therefore it sometimes did not give the desired appearance of disappearing over the top of a hill and often appeared to be directing the aircraft into the rising ground. This could be solved by cross reference to the terrain database and clipping the tunnel symbology at the appropriate distance from the aircraft.

In addition, it is proposed that three dimensional audio signals should be evaluated for obstacle cueing.

The demonstration also highlighted the importance of optimising the control strategies used in conjunction with flight guidance symbology. Control law developments could include a coupled autopilot height hold mode and an airspeed hold to reduce the workload associated with following the flight director.

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References

1. Ellis, S.R., and McGreevy, M. (1983). Influence of a perspective cockpit traffic display format on pilot avoidance manoeuvres. Proceedings of the 27th Annual Meeting of the Human Factors Society, pp 762-766, Santa Monica , CA, Human Factors Society

2. Calhoun, G.L., Janson, W.P., andValencia, G. (1988). In Riding the Wave of Innovation, Proceedings of the Human Factors Society 31st Annual Meeting,Volume 2, pp 1398-1402, New York City, October 19-23, 1987. *The Human Factors Society, Santa Monica, CA.*

Bibliography

Brown, M. and Harris, C.J., (1994) Neuro-fuzzy Adaptable Modelling and Control. Systems and Control Engineering, Prentice Hall, Hemel Hempstead, UK.

Chui, C.K. and Chen , G. (1987) *Kalman Filtering with Real Time Applications*, Vol 17, Springer Series in Information Sciences, Springer-Verlag, Berlin Heidelberg.

Doyle, R.S. & Harris, C.J., (1996) Multi-sensor data fusion for helicopter guidance using neuro fuzzy estimation algorithms. The Aeronautical Journal of the Royal Aeronautical Society, June/July , Vol 100 (no 996) pp 241-251

Abbreviations

ADS	Air Data System
AKF	Adaptive Kalman Filter
AMN	Associative Memory Networks
DKF	Decentralised Kalman Filter
EMS	Emergency Medical Services
GPS	Global Positioning System
HDD	Head Down Display
HMD	Helmet Mounted Display
HMI	Human Machine Interface
HUD	Head Up Display
IFR	Instrument Flight Rules
INS	Inertial Navigation System
ISIS	Image Speech and Intelligent Systems Group
KF	Kalman Filter
MSDF	Multi Sensor Data Fusion
OAS	Obstacle Avoidance System
TCAS	Traffic Alert and Collision Avoidance System
VFR	Visual Flight Rules
VV	Velocity Vector