ABSTRACT

This paper presents the design of an intelligent combat maneuvering system capable of aiding operators of unmanned vehicles in critical situations to defend themselves from attack and destruction from either manned or unmanned air threats. The system consists of an intelligent associate system which monitors environmental constraints and interacts with the operator to maintain situational awareness. The architecture uses pre-computed maneuvers based upon the dynamics of the vehicle. The goal of the system design is to provide on-board reactive behaviors and variable levels of autonomy that allow the operator and the vehicle to collaborate in the execution of aggressive combat maneuvers.

INTRODUCTION

On April 22, 2008 a Georgian Unmanned Air Vehicle (UAV) was attacked by a Russian MiG 29. The UAV operator captured the event using the vehicle’s on-board camera. From the video it can be seen that the remote operator only had about 3-4 seconds to perform a counter-measure once a missile launch was visually detected. The operator did not perform any evasive maneuvers and the UAV was shot down.

This paper describes the design of an intelligent mission planner capable of selecting and autonomously executing aggressive maneuvers. The system will aid operators in critical situations by allowing them to quickly replan vehicle trajectories. The architectural design attempts to merge the modeling of high-level plans and goals of a pilot with the low-level control processes required for the efficient control of air vehicles (Figure 1). The system will consist of an intelligent associate system which monitors environmental constraints and interacts with the operator to maintain situational awareness. Associate systems are in the family of intelligent agents except they are designed to work alongside human operators. Associates support the operator in making decisions and are capable of autonomously executing tasks on behalf of the operator. The system will also consist of a library of pre-computed maneuvers based upon the dynamics of the vehicle. The pre-computed maneuvers allow the operator to plan trajectories that take full advantage of the vehicles capabilities.

In situations where the operator only has a few minutes to replan a mission due to an unexpected threat, the intelligent combat maneuver system will help the operator quickly assess the situation, recommend a sequence of evasive maneuvers, wait for the operator’s decision and then execute the maneuvers. If the situation only allows a few seconds to respond, the system will be capable of autonomously selecting and executing an appropriate sequence of maneuvers. The design...
supports flexible authorization levels that allow the operator to control how and when each maneuver can be autonomously executed.

The intelligent combat maneuvering system will be designed to complement the existing mission planning and control systems. It is not intended to replace the aircraft’s onboard autopilot or traditional mission planning systems such as the Air Force Mission Support System (AFMSS). The goal of the system is to provide on-board reactive behaviors and variable levels of autonomy that allow the operator and the vehicle to collaborate in the execution of aggressive maneuvers for single vehicles as well as for multiple vehicles.

INTELLIGENT COMBAT MANEUVERS

BACKGROUND – The control of Unmanned Aerial Systems (UAS) in dynamic combat environments remains a challenging problem. There are roughly three approaches to controlling unmanned vehicles: manual control, semi-autonomous control and autonomous control [2]. An example of manual control can be seen in the control of the Predator UAS. A remote operator manually controls the Predator throughout all phases of flight. The human operator determines the flight path and sends low-level commands to the control surfaces in order to fly the airplane. The Predator does have an autopilot but it is not capable of autonomous behaviors required for dynamic combat environments [3]. A problem with manual control is that the Predator pilots have suffered from high workload and fatigue due to the tedious nature of remote, manual control [4].

Autonomous control consists of planning and programming missions in advance. An example of autonomous control is the Global Hawk. Each mission is planned in detail with a set of pre-programmed flight paths which the vehicle autonomously executes [5]. The human operator is a supervisor or mission manager that simply monitors the aircraft as it executes the pre-programmed tasks. This approach works well for reconnaissance missions but it is not effective for complex and dynamic environments encountered in combat missions. The limited range of automation does not support reactive maneuvering and evasion. A known problem with highly autonomous control is that the operator can become complacent and lose situational understanding [6]. If the operator is not constantly involved in the control of the vehicle, the operator may lose situational understanding and may not be aware of critical changes in the environment. During long cruise phases of flight, it is very easy for an operator to become inattentive due to the lack of events or tasks to perform.

Human interaction with autonomous systems is more complex than simply switching the automation ON or OFF. For the best performance, operators need to be involved at different levels of control. If the operator is simply monitoring tasks, optimal performance has been shown to occur at moderate levels of interaction according to the Yerkes-Dodson Law shown in Figure 2 [7]. For optimal performance, autonomous systems need to support multiple levels of interaction [8]. Sheridan outlined a scale (Table 1) of automation from 1 to 10 where each level represents more automation [9]:

Unmanned Combat Air Vehicles (UCAV) such as the X-45C (Figure 3) require more levels of automation than simple manual or fully autonomous control due to the nature of their missions. Unlike high altitude reconnaissance aircraft, UCAVs operate in dynamic combat zones where the environment is always changing. Despite our best efforts, almost all missions require some replanning. Unmanned combat air vehicles will need to react to unforeseen threats as well as handle multiple unplanned targets and events. Pilots of unmanned combat vehicles must control their vehicles on both long, routine cruise phases of flight as well as short, dynamic phases encountered when entering combat zones. Operators must be alert and aware of the current situation during all phases of flight. If a threat “pops up” as in the case of an incoming missile, operators will be required to execute an unplanned maneuver. If the operator is caught off guard or does not have enough time to execute a maneuver, the mission planner onboard the vehicle should be capable of reacting to save the aircraft. An on-board intelligent control system could detect the in-bound missile and recommend a course of action based upon the vehicle’s current flight profile and trim.
In order to maintain the operator’s situational awareness and enable multiple levels of automation, a different control paradigm needs to be supported [10]. This approach has several key requirements:

- **Single Operator, Multiple Vehicles**: The new model must support a single operator controlling multiple air vehicles.
- **Variable Autonomy**: The system should preserve the operator’s freedom, authority and accountability while allowing for autonomous behaviors within each vehicle [11].
- **Mixed Initiative Behavior**: The system should support the blending of human direction and autonomous behaviors.
- **Bounded Autonomy**: Each UCAV should have the ability to autonomously react to its changing environment but within the bounds specified by a supervising operator.

A vehicle mission planner that supports mixed initiative and bounded autonomy provides a powerful capability to assess and plan trajectories onboard the vehicle. This will allow each vehicle to recommend and execute autonomous maneuvers without exceeding the tactical plans and goals set by the operator. These capabilities enable on-board reactive behaviors and variable levels of autonomy that allow the operator and the vehicle to collaborate in the execution of aggressive maneuvers [12].

**GUIDANCE PROBLEM** – One of the primary requirements for a vehicle mission planner is to plan trajectories that allow the vehicle to safely maneuver through complex environments. The conventional approach is to decouple the navigation and control of the aircraft into a path planning problem and a path following control problem. A planner first calculates a safe trajectory and then transmits this path to the vehicle. It is then up to the vehicle’s feedback control system to attempt to follow this path. The vehicle’s dynamics or constraints are usually not considered at all by the planning system. In some situations, the vehicle can actually travel in oscillating paths as it attempts to match the planned trajectory. As a result, the vehicle may not have a safe margin for nap-of-the-earth routes or for flying in tight formations.

A number of approaches have been developed for the coupled navigation and control problem. In some cases, the constraints on the vehicle’s motions are completely ignored and it is assumed that the vehicle is operating in very open spaces [13]. The vehicle is essentially free to move in all directions. Of course, this assumption will not work with complex missions in dense environments. Another popular technique for managing the motion of vehicles is to limit the aggressiveness by smoothing the trajectories [14]. This allows a margin of safety when planning trajectories around obstacles. However, the planned paths are smoothed across the entire motion plan. This approach does not take advantage of the maneuvering capabilities of vehicles. The onboard planning system needs to be able to execute real-time trajectory changes that incorporate the vehicle’s dynamics as well as the mission and environmental constraints.

**MANEUVER-BASED FLIGHT CONTROL** – In order for a mission planner to recommend maneuvers, the maneuvers need to be in a symbolic form which the planner can use. Unfortunately, the dynamics of an aircraft are typically represented by a system of ordinary differential equations. In order to steer a vehicle to a specific goal, a control law must be computed that meets a specified performance objective. This is a very difficult problem for realistic aircraft due to the complex aerodynamic dependencies. Once vehicle and mission constraints are added to the problem, the state space becomes very large and the “curse of dimensionality” makes the solution intractable [15].

One solution to this problem is a hybrid vehicle-modeling strategy such as the maneuver automaton introduced by Frazzoli et al. [16]. The maneuver automaton approach replaces the continuous dynamic equations with a finite-state hybrid system. The system dynamics are formulated in the maneuver space of the vehicle and represented in qualitative terms as motion primitives. The maneuver automaton encodes all of the relevant information about a vehicle’s dynamics and flight envelope constraints.

This flight control concept is very different from standard waypoint navigation. Instead of defining a trajectory with waypoints and then giving the aircraft’s flight control system the responsibility of following the trajectory, the maneuver automaton approach defines trajectories in advance based upon the vehicle’s dynamics. Maneuvers can then be created in real-time by defining a sequence of trajectories. This allows trajectories to be planned that incorporate the vehicle’s dynamics and capabilities.

The primary class of motion primitives are steady state trim trajectories. Steady state trim maneuvers can be viewed as an “equilibrium” vehicle state. During the trim states the vehicle velocities and the control inputs are constant [16]. The vehicle is not pulling a high G turn or changing its attitude. Examples of steady state trim maneuvers include: steady level flight, constant...
climb/descent, constant level turn and constant climb/descent turn.

Using the trim trajectories, more maneuvers can be created. These "basic" or primitive maneuvers can be viewed as transitions from one trimmed state to another. Essentially, the vehicle can always be considered to be executing either a steady trim motion or a maneuver between trim states. The maneuver automaton encodes the set of possible trim motions and the interconnecting maneuvers as a state-machine. The resulting model can be conveniently represented as a directed graph as in Figure 4. The circles represent trim states and the arcs between states represent maneuvers. Examples of basic maneuvers are simple heading changes, climbs, descents and loops. From the state diagram it can be seen that basic maneuvers begin and end with a trimmed trajectory. More complex maneuvers can be created by sequencing basic maneuvers and trim trajectories together. Figure 5a shows a vehicle performing a basic maneuver by transitioning from one trim state to another trim state [18]. Figure 5b shows a more complex sequence. Examples of complex maneuvers are the Offset, Immelmann, Split S, Hammerhead and Low Yo-Yo.

![Figure 4 Maneuver Automaton [17]](image)

ASSOCIATE SYSTEMS – An associate is an intelligent agent that helps a human operator to perform a complex job. Associate systems elevate the operator to the role of the decision maker or mission manager. Rather than have the operator manually control every servo and actuator of the vehicle, associates enable the operator to focus upon higher-level tasks that are critical to the success of the mission.

Associate systems support active information collection, situation assessment, planning, plan execution and coordination with multiple human operators and other associates. They can be designed to assist with all command and control tasks of a vehicle. As a result, tasks do not need to be allocated exclusively to the human operator or to the associate, but can be allocate to both the human operator and the associate. An associate architecture enables collaboration of multiple agents regardless of whether the agent is a human operator or an associate system [19,20].

An associate system supports multiple levels of automation but there is a distinct difference between conventional automation and the autonomous behaviors of an associate system. Conventional automation attempts to replace human control and decision-making. Intelligent associate systems do not attempt to replace human control but rather augment human control. Associate systems operate as intelligent aiding systems that attempt to enhance the operator’s judgment and responsibility.

Every task that an associate executes is under the supervision of a human operator. The operator can assign authorization levels to each plan or action. Example authorization levels include manual, permission, veto and autonomous. In manual mode, the operator has full control of the task execution. The associate system may propose a plan in permission mode but may not execute it without explicit authorization from the operator. In veto mode, the associate is authorized to execute a proposed action if the operator does not veto the action within a set timeframe. In autonomous mode, the associate system is authorized to select and execute proposed actions.

Knowledge Representation –While there is no widely accepted definition of intelligent behavior in its detail,
there is broad agreement about several of its features. Intelligence is a dynamic system that takes in information about the world, abstracts regularities from that information, stores it in memories, and uses a priori knowledge about the world to form goals, make plans and execute plans. The core knowledge of associate systems is represented in two graph data structures referred to as concept node graphs (CNG) and plan-goal graphs (PGG).

Figure 6 Plan Goal Graph

Plan-goal graphs - PGGs store the actions that either a vehicle or pilot can perform. Since the maneuver primitives represent actions they will be implemented in the plan-goal graph. An example of a generic PGG can be seen in Figure 6.

The PGG contains two types of nodes: plans and goals. Plan nodes are always children of a goal node. The plan nodes represent operations and their parent goals represent the intended effect. At the top level of the PGG are abstract goals. These represent desired behaviors that are highly aggregated and abstract. As the levels of the PGG are traversed downwards, each layer becomes more concrete and specific. The lowest level of the PGG consists of primitive actions that can be directly performed by a pilot or vehicle. Maneuvers will be implemented at the lowest level or "leaf level" of the PGG tree structure.

The PGG allows alternative maneuvers to be defined for a specific goal in the form of children plans under a parent goal. The links between the nodes contain constraints that determine if the maneuver is feasible. A typical constraint would simply be airspeed above or below a designated threshold. Vehicles maneuver better at different speeds and some maneuvers require a minimum airspeed in order to be successfully implemented.

Concept Node Graph - The CNG is a hierarchical description of the world state. It represents the associate’s beliefs and trends about the environment. It is designed to increase in abstraction and aggregation when traversing up the graph, as well as show dependencies between concepts in the form of links (Figure 7). In a concept graph, sensor data is inserted into the concept graph in lower level nodes. Value is added to the sensor data by aggregating and abstracting the raw data to form higher level conclusions. An example of aggregation would be determining a vehicle’s range based upon its fuel level, speed and payload weight. An example of abstraction would be calculating the time a vehicle has at a target location based on the vehicle’s current range capability.

Figure 7 Concept Node Graph

Vehicle and environmental constraints will be implemented in the concept-node graph. As sensors on the vehicle detect objects in the environment, the objects will be inserted into low-level nodes of the graph. As the vehicle moves through the environment, the location of these objects will be updated. If the range to an object falls below a specific threshold, the object can be abstracted and be classified as an obstacle. The existence of an obstacle concept in the CNG can trigger a new goal to become activated in the plan-goal graph. In this example, the new goal is to avoid obstacles and a plan would be selected to achieve this goal. The plan would result in the selection of a maneuver that meets the constraints of the vehicle, mission and environment.

Knowledge Processes – Several knowledge processes operate on the plan-goal and concept graphs structures.

Planning Process – A dynamic planning process operates on the knowledge to select the best plan to achieve a goal. At design time, the plan goal graph is organized from high-level plans and goals down to primitive actions. At run time, the dynamic planner uses a skeletal planning approach to compose courses of action that can be executed in parallel by the operator or one or more vehicle associate systems. This algorithm is in the family of Partial Order Planners, and while not a provably optimal planner, it is known for its speed and heuristic correctness. It is capable of simultaneous plan generation and plan execution. The planning algorithm is specifically organized to permit continuous human interaction during plan generation and plan execution. This enables an associate system to continue to recommend plans to an operator even though the operator may have rejected the associate’s current course of action.

Intent Interpretation Process – While planning is done through PGG decomposition from high-level plans and goals to primitive actions, intent interpretation works “up” the PGG by observing actions and then attempting to identify the high-level plan associated with that action. This enables an operator to communicate his intent...
using abstract plans. For example, a UCAV operator can send a mid-level plan or goal to an intelligent associate on a vehicle without explicitly transmitting the higher-level plans and goals. Once the node is received, the vehicle associate can infer the higher level plans and goals the operator is attempting to accomplish. The dynamic planner on the vehicle will complete those portions of the overall plan that were omitted. A benefit of this capability allows associate systems to operate with poor or intermittent communications [10].

Information Management – Since the associate system has knowledge of the operator’s current plans and goals, this allows the system to manage information that is relevant to the operator’s current task. By monitoring the vehicle’s state along with environmental conditions, the associate knows the context in which the operator’s plans are operating. If the operator attempts to execute a plan that conflicts with an environmental or vehicle constraint, the associate system can display this conflict to the operator.

Situation Assessment Process – An associate system independently analyzes the situation based on data collected from the vehicle sensors and communicated to the associate remotely. Situation Assessment provides a knowledge-based approach to the interpretation of real-time data by dynamically maintaining abstract concepts that describe the situation as understood by the associate.

Error Handling – Unlike conventional error handling approaches that make only limited use of the semantics of a user input to detect errors, the associate’s Error Management process provides robust error detection for single and multi-user applications. The Error Management component works with the intent interpreter to detect operator errors (incorrect execution), user intent errors (mistakes, correct execution of the wrong task) and breakdowns in coordination across multiple users. Exceptions raised by the intent interpreter are analyzed by the Error Management component to determine the type of error and its best remediation.

Decision Aiding – Combining the knowledge processes with the plan-goal and concept graph representations, provides a powerful decision aiding system. The associate system monitors the environmental conditions, mission objectives and operator intentions. Based on the current situation, the associate system can offer context-sensitive plans to the operator. The operator’s authority is always preserved since he can accept or reject the recommended actions. If the operator performs actions that are outside of the current scope of plans, the associate system can infer the operator’s intentions and continue to aid the operator with the current scope of plans and goals.

Mixed Initiative – Mixed initiative behavior is described as the smooth blending of associate actions with operator actions. The hierarchical and abstract representations in the PGG and CNG allow the operator and the associate system to communicate at high-levels of abstraction. The operator is free to interact with the system at very low levels such as lowering the landing gear or the operator can simply give high level commands to the vehicle such as “return to base”.

A vehicle mission planner based upon an intelligent associate would provide a powerful capability to assess and plan maneuvers onboard the vehicle. The mission planner would be able to recommend and execute autonomous maneuvers without exceeding the tactical plans and goals set by the operator. Combining maneuver automaton and intelligent associates allows the operator and the vehicle to collaborate in the planning and execution of intelligent maneuvers.

INTELLIGENT MANEUVERS – An intelligent maneuver is a maneuver that is executed at the appropriate time as part of a plan to achieve a specific goal. The combination of maneuver automaton and intelligent associate systems results in a design capable of recommending and performing maneuvers that incorporate the vehicle’s dynamics, the environmental constraints and mission goals. Selected maneuvers are situated to the current context of the vehicle and the mission.

The selection of maneuvers can be viewed as a sequential decision process. At the start of each decision step, the vehicle is flying in one of the trim modes. The guidance problem is then reduced to deciding at each decision step whether to stay in the current trim mode, transition to another trim mode or to execute a specific maneuver. Each maneuver has its own constraints for execution. If the entry conditions for the maneuver are not satisfied along with vehicle and environmental constraints, the maneuver cannot be selected.

If the associate system activates a goal to "Turn Around", there will be several plans and maneuvers which can satisfy this goal. A few example maneuvers are a simple U-Turn, Immelmann, Hammerhead or a Split S. The Immelmann is shown in Figure 8. The associate’s plan-goal graph encodes the constraints for performing this maneuver as well as the high level goals that it achieves. The Immelmann maneuver tradesairspeed for altitude during a 180 degree change in direction. This maneuver results in the vehicle gaining altitude but loosing speed. As a result, this can be a good offensive maneuver but a poor defensive tactic due to the lower speed of the aircraft.

Figure 8 Immelmann Maneuver
The Split S maneuver is essentially an Immelmann in reverse. It trades altitude for airspeed and reverses direction. In combat or high threat situations, neither maneuver may be appropriate due to the speed and altitude tradeoffs. By modeling the situational context and the vehicle constraints, an associate system will possess tactical knowledge and be able to determine which maneuvers are appropriate and which ones are simply too risky.

**Tactics** — The intelligent combat maneuvering system uses plans and goals to model the tasks of the operator and the vehicle. This is a type of knowledge-base system. The design of the plans and goals will be developed from the experience of highly trained pilots [21]. Subject matter experts (SME) will be interviewed to determine how they would perform defensive and offensive maneuvers and under what circumstances. Their experience will be encoded in the associate's plan-goal graph. This capability will allow an intelligent combat maneuvering system to have knowledge of tactics and to determine which maneuvers are appropriate or inappropriate. Capturing the experience of an expert also has the benefit of training and supporting inexperienced operators in making critical decisions during high stress situations.

**Maneuver Automaton Limitations** — One of the criticisms of the maneuver automaton approach is that the vehicle motions are limited to a finite set of motion primitives. Depending upon the required mission tasks and the environment, a small set of motion primitives may not be sufficient. More motion primitives can be calculated providing a higher resolution search space, but this can lead to search problems [17].

The intelligent associate can reduce the search problem by selecting a subset of maneuvers that meet the vehicle, mission and environmental constraints. For example, based upon the vehicle’s speed specific maneuvers can be ruled as infeasible and will not be considered during the planning process. This reduces the problem complexity and required computation time. Conversely, the associate can also activate a higher resolution set of maneuvers if the situation demands it.

**FUTURE WORK** — A major assumption that enables the development of a maneuver library is that of time invariance. The vehicle dynamics are assumed not to change during the mission. In reality the dynamics may change as fuel is used, ordnance is dropped or flight surfaces are damaged. An active area of research is learning the vehicle’s control dynamics in real-time during a mission. An important extension of this work would be quantizing the newly derived vehicle dynamics into maneuver automaton that would support high level planning and contingency management.

**CONCLUSION**

Operators of UAV systems are often faced with events that were not anticipated. Malfunctions, retasking, enemy actions, intrusions by friendly forces and other events may require a mission to be replanned. This paper describes the design of an intelligent combat maneuvering system capable of aiding operators in critical situations to defend themselves from attack and destruction. The system consists of a library of achievable maneuvers that can be executed based upon the current environmental threats and current state of the aircraft. In critical situations, the operator may only have seconds to make a decision. The intelligent combat maneuver system can help operators to make experienced decisions in critical, high-stress situations. The variable autonomy provided by the system allows the operator to increase manual intervention in systems that otherwise would be fully autonomous. In situations where the operator does not have time to intervene, the intelligent combat maneuver system is capable of autonomously selecting and performing appropriate maneuvers. The intelligent combat maneuver system provides on-board reactive behaviors and variable levels of autonomy that allow UCAV operators to execute missions effectively for single vehicles as well as for multiple vehicles.

**REFERENCES**


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