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Demonstration of Effects-Based Operations Using Fully Autonomous Heterogeneous Vehicle Swarms

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Abstract— **Effects-based operations have been demonstrated on hardware to realize practical and autonomously performed behaviors utilizing a variety of vehicle platforms including ground, water surface, and aerial vehicles. The heterogeneous vehicle swarms enact a variety of cooperative behaviors autonomously, using reactive, effects-based algorithms and broadcast-only, decentralized communications. Control is achieved through the use of stigmergic potential fields, a form of cooperative motor schema behavior based upon mathematical functions that are associated with entities in the operational environment of the vehicle. The video demonstration shows footage from actual hardware tests that have demonstrated empirically how reactive swarming behaviors using stigmergic potential fields can offer robustly sufficient behavior with improved total system survivability and total operational effectiveness, particularly under dynamic environmental and operational conditions.**

***Index Terms*— Command and Control, Robot Programming, Swarm, Behavior, Intelligent Agents, Multi-Robot, Intelligent Agents**

I. INTRODUCTION

Effects-based operations (EBO) [4] are a primary focus of ongoing research on the means by which warfare will be conducted in the new century. EBO provides a basis for coordinated, joint combat operations while freeing the operator of autonomous vehicles from the tedium of human-in-the-loop control.

> *“EBO consists of a set of processes, supported by tools and accomplished by people in organizational settings, that focuses on planning, executing, and assessing military activities for the effects produced rather than merely attacking targets or simply dealing with objectives”.* [6]

Important parameters within EBO include the accurate discernment of the commander’s intent and a rapid, flexible operations assessment cycle. In the presented approach, the EBO command and control metaphor has been extended to unmanned vehicles by employing *effects-based control* in which operators provide operational objectives that are acted upon by ad-hoc coalitions of unmanned vehicles. Each autonomous agent is tasked to independently discern user intent, assess the state of its world view and then devise a course of action to support operational orders. Progress toward the desired effect is continually assessed, while timely alerts and situational intelligence are provided to the system users. This approach differs from current unmanned vehicle control, in which trained operators use explicit, detailed tasking to control individual vehicles and exfiltrated data is analyzed by rear echelon analysts.

II. APPROACH

The central theme of our approach is the use of stigmergy to achieve effects-based control of cooperating unmanned vehicles. Stigmergy is defined as cooperative problem solving by heterarchically organized vehicles that coordinate indirectly by altering the environment and reacting to the environment as they pass through it. The alterations to the environment need not be physical, only virtual and communicable to peers. Stigmergy is accomplished through the use of locally executed control policies based upon potential field formulas. These field formulae, called Stigmergic Potential Fields (SPF), are used to coordinate movement, transient acts and task allocation among cooperating vehicles.

A hierarchical control architecture is used (Fig. 1). Each layer is an independently executing control process. Upper layers exercise control over lower layers by asynchronously altering the objectives of the lower levels. The top-most layer, Inter-modal Behavior, controls transitions among other behaviors. The Intra-modal behavior realizes specific behavioral functions such as regulation of transient actions like vehicle course and speed. Beneath the Intra-modal layer, the Reflexive behavioral layer provides collision avoidance and maneuvering in and around near-field obstacles while pursuing the course ordered by the Intra-modal layer.

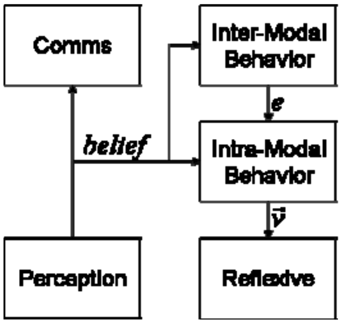

Fig. 1. Vehicle Control Architecture

All vehicle decisions are made locally. Coordination among vehicles occurs through the sharing of knowledge. Knowledge is shared implicitly through co-observation, or

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explicitly through direct or indirect communication. Cooperation through co-observation occurs when vehicles with overlapping sensor coverage observe each other's actions. Cooperation through implicit means occurs when vehicles observe the effects of each other's actions. Cooperation by explicit communication is achieved through an *influence network*.

The influence network is an addressless communication mechanism by which vehicles share knowledge using periodic omni-directional broadcasts. Transmission occurs without knowledge of the recipient or the information's utility. Received information is used to update a vehicle's world model. This communications technique allows knowledge to propagate asynchronously across the swarm without the need for a continuous, high quality of service, routed network.

III. DEMONSTRATIONS

The described techniques have been used to demonstrate useful behaviors on autonomous ground, aerial, and water surface vehicles with great success. In September of 2004, a demonstration at Philips Airfield at the Aberdeen Proving Grounds was completed in which four autonomous ground vehicles and two autonomous air vehicles were used to achieve a series of C^4ISR objectives provided asynchronously by three uncoordinated operators exercising effects-based control. The main focus of these demonstrations was the testing of the behaviors and control algorithms, not necessarily the acquisition of data from sensors. As a result platform sensing strategies were contrived to support the objectives of the demonstration.

For this demonstration, the four autonomous ground vehicles provided a perimeter patrol for a mock power plant, a high value asset while a convoy entered the operational area. Two UAVs provided surveillance and cover for the convoy and detected a group of potential hostile targets at an intersection. The ground vehicles responded to this possible thread by forming an interdiction line between their asset and the intersection. One vehicle was specially equipped with the means to classify the group as hostile or friendly (in this case distinguished by an audible tone). This vehicle autonomously changed to the appropriate behavior and classified both friendly and hostile targets. This information was inherently communicated to all autonomous peers and system users. The convoy stopped while the rest of the ground vehicles swarmed on the location to pursue the hostile target. After neutralization of the threat, the convoy operator entered an order to search the intersection for IEDs. At the same time, another used at the power plant placed an order to search the area surrounding the high value asset. The vehicles self organized and completed both objectives simultaneously, even when one of the vehicles experienced a hardware failure. The other vehicles compensated for the loss with no user intervention.

Since this highly successful demonstration, these algorithms have been used to control UAVs in the completely autonomous sampling of a simulated chem/bio weapons release at Dugway Proving Grounds (DPV). This test was completed using a dragon eye UAV outfitted with a particulate collection apparatus in the nose. A standoff sensor was used to gauge the approximate location of a simulated agent release. These coordinates were used to define a search area for the UAV which then autonomously surveyed the area, successfully collecting samples of the release agent, and returning the material for analysis.

Most recently these algorithms have been used to control search and pursuit behaviors for a 40 ft. unmanned sea surface vehicle. These tests show the versatility and adaptability inherent in the EBO control approach presented.

IV. CONCLUSION

The employment of highly autonomous unmanned vehicles for response to effects-based control has been demonstrated. Given this evidence, the utilization of swarms of effects-based vehicles to accomplish varied military objectives should not be viewed as a distant goal. In contrast, we have demonstrated how reactive swarming behaviors can produce *robustly sufficient* behavior offering improved total system survivability and total operational effectiveness, even under dynamic environmental and operational conditions.

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