Holarchical Systems and Emotional Holons: Biologically-Inspired System Designs for Control of Autonomous Aerial Vehicles

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ABSTRACT

The BEES (Bio-inspired Engineering for Exploration Systems) for Mars project at NASA Ames Research Center has the goal of developing bio-inspired flight control strategies to enable aerial explorers for Mars scientific investigations. This paper presents a summary of our ongoing research into biologically inspired system designs for control of unmanned autonomous aerial vehicle communities for Mars exploration. First, we present cooperative design considerations for robotic explorers based on the holarchical nature of biological systems and communities. Second, an outline of an architecture for cognitive decision making and control of individual robotic explorers is presented, modeled after the emotional nervous system of cognitive biological systems.

Keywords: Holarchy, Biologically Inspired, Emotional UAV Flight Control

1. INTRODUCTION

The BEES (Bio-inspired Engineering for Exploration Systems) for Mars project at NASA Ames Research Center has the goal of developing bio-inspired flight control strategies to enable aerial explorers for Mars scientific investigations [1]. The research presented here will focus on unmanned autonomous aerial vehicles (UAVs) for Mars exploration. The significant advantage afforded by UAVs over ground-based robotic explorers has generated recent interest and research into understanding and overcoming the engineering challenges of fielding flight vehicles in the Martian atmosphere [2]-[7]. These advantages include a higher degree of mobility, instrument access to areas that cannot be traversed on the ground, and coverage of a larger area of the Martian surface [8]-[10]. Section 2 presents ongoing BEES for Mars implementation.

Biologists address the natural world in levels of functional groupings, each emergent from its component levels. In this paper, we present our work on bio-inspired technology for robotic Martian explorers. In functional decomposition of bio-inspired concepts, each layer of structure and function mimics a biological counterpart. While typical applications of biological inspiration ideas tend to isolate a single aspect of the natural world for emulation, such as a neural network model of brain function [11][12] or swarm concepts based on insect colonies [13], the BEES for Mars project integrates multiple levels of bio-inspiration. In section 3, elements and classifications of the biological holarchy are defined, and their applicability to design of robotic communities is discussed. The control and decision making of aerial explorers is designed after cognitive models of emotion in biological organisms. While the role of emotions in the cognitive process is still a hotly debated area of research in scientific fields such as neuroscience and psychology, research suggests that emotions are the fundamental basis for rational decision making by organisms, and provides adaptability in making decisions when faced with uncertainty [14]-[17].

Through the modeling of emotions, this endeavor attempts to capture the essence of rational and adaptive decision making in organisms, with the aim of quantifiably outperforming unemotional counterparts in goal-oriented tasks when faced with uncertainty. Adaptive ability is critical in a remote environment where real-time human control of flight vehicles is not possible. In such scenarios, the inability for the system to adapt quickly to unpredicted adverse situations and other uncertainty will result in the unrecoverable loss of the aircraft resource. Section 4 will present a defense for utilizing an emotional model for flight controls, outline previous work in this field, and present an architecture that is currently under development that utilizes an emotional nervous system to control all aspects of UAV behavior, from decision making to navigation and low level automatic controls. Section 5 will outline the development strategy and road map for the implementation of these research ideas.

2. FIRST STEP: MISSION CONCEPTS & BIO-INSPIRED BEHAVIORS

Preliminary work on the BEES for Mars effort focused on the definition of bio-inspired mission concepts and flight "behaviors" that would successfully effect Mars aerial explorer demonstrations with terrestrial surrogate vehicles.

Mission concepts in [18] derive from situations in the biological world that are oriented toward "search and find" requirements: a mission using dropped aerial probes based on dissemination and survivorship curves and a terrain-influenced search trajectory derived from predation strategies. A small compendium of bio-inspired behaviors was defined for an aerial vehicle. These behaviors were categorized into general groups: UAV "primitive" tasks, observations, actions, and planning. The use of stochastic search strategies was also emphasized in this preliminary work.

Figure 1 illustrates an early BEES for Mars implementation demonstrating conventional search and find behaviors. The demonstration used a 2-meter wingspan UAV system that had been enhanced to include a ground based adaptive decision component. This decision component allowed the aircraft command sequence to be altered based on images that were recognized from video downlinked from the aircraft.

The mission entailed searching for a target (in this case a large orange tarp on the ground), visually recognizing the target, and dropping a small aerial imaging probe at/onto the position of the target, before resuming its search.

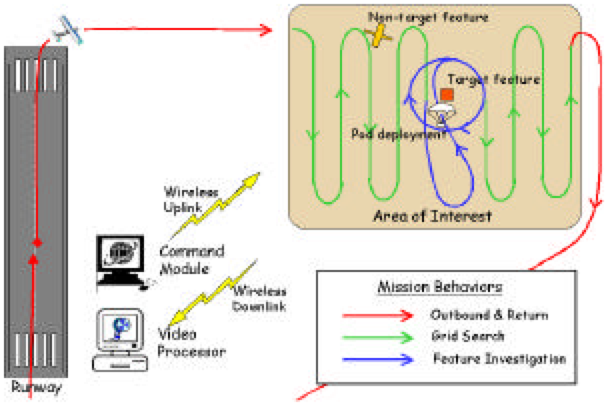

Figure 1. Early Search and Find Behavior Demonstrations

Definition of flight behaviors for Mars aerial explorers is only the first step towards developing the autonomous system technology required for Mars exploration missions. It is also necessary to develop techniques to evaluate situations, make decisions, and implement behaviors while following the general outlines of the mission plan. These requirements will entail investigating ways in which intelligent systems evaluate, interact and self organize, both individually and with other aerial explorers and ground components.

Again, we turn to nature for concepts that may inspire solutions. The use of holarchical design shows promise as an architecture in which intelligent systems can interact as a community. Our research also shows that decision-making and control in intelligent systems may be enhanced by the introduction of emotional models. An emotional holon, a rational intelligent system capable of interacting within a community of other aerial explorers is the goal of our research.

3. HOLARCHICAL DESIGN CONSIDERATIONS FOR ROBOTIC COMMUNITIES

The words holon and holarchy were coined by Arthur Koestler in the 1970's [19]. A holon expresses a dualistic nature as both whole and part; each level of a holarchy functions as an independent unit and acts as component of a larger, more encompassing whole. In contrast, a hierarchy refers to a pyramidal structure of power relationships. Elements of hardware or software development are familiarly defined in terms of functional hierarchies, where components and sub-components contribute to overall system function. In a hierarchical architecture, components often lack meaningful function outside the context of the larger system function. Alternatively, a holarchical architecture approach strives to present a balance between near-equal, near-independent but interacting, automated agents working across several levels of operation and cooperation/interdependence of individual and multiple robotic systems.

The natural world comprises a holarchy, which spans the sciences of sub-atomic physics, through chemistry and biology to astronomy and cosmology. A molecule is a whole unit, whose function emerges from the types, states, and relationships among its component atoms, each whole unto themselves. The organelles inside a living cell have their own existence as structures built of macro-molecules but also contribute to the overall life and function of the cell. In the science of biology, the holarchy continues through tissues, organs, and organ systems inside the individual organism; proceeding outward from the organism, the biological holarchy includes populations, communities, biomes, culminating in the biosphere.

Biological Community Holarchies

The designs of autonomous planetary explorers are suited to their environment and their function. While biological species adapt to their environments through evolution, and robotic explorers are created through a structured design process, the individual robot is analogous to the organism in the holarchical systems approach.

Nature offers infinite variability and categorical statements can only be simplifications or generalizations. A population is a group of organisms of the same species living in the same area; members of a population interact for reproduction, use of resources, protection, social effects, and other purposes. Depending on the species, the individuals may compete with one another or cooperate but all occupy the generally same niche in the ecosystem. In a bio-inspired technological holarchy, the population comprises multiple units of the same design, serving the same function.

In BEES for Mars, the number of autonomous aerial vehicles is a limited resource and so hardware implementation is constrained to one or two vehicles. With continuous vehicle-to-ground communication, it is possible to create "software-in-the-loop" simulations, where the onboard processor may be fed information allowing it to respond to virtual stimuli. Since all control algorithms are programmed on desktop processors before conversion to flight code, virtual vehicles will behave according to the same rules as hardware vehicles. Most of the members of a large population will be simulated vehicles.

In nature, a community is made up of populations of many species living in the same area, interacting and using local resources. An organizing principle for the study of biological communities is the flow of energy through the system. With the exception of a few deep-sea thermal vents, the ultimate source of all the energy used in the biological world is the sun. There are three basic stages in the cycle of energy transformation in biological communities, represented by producers, consumers, or decomposers.

Producers are organisms which have the ability to capture the incoming energy of the sun and store that energy in the chemical bonds of their tissues through photosynthesis. Plants are familiar producers in terrestrial ecosystems; trees, for example, store great amounts of energy in their wood. Other producers are phytoplankton in the ocean, photosynthetic micro-organisms on land, and kelp and other algae. Consumers utilize the energy stored in other living things for activity and to build their own tissues. Primary consumers eat producers, while secondary consumers eat other consumers. The "food chain" is a familiar metaphor, with lions, zebras, and grasses being a favorite example. However, when the varied diets of real animals are examined, the relationships among consumers and producers form a complex food web. A third and very important element in the processing of energy and material in a community are the decomposers. Decomposers release the energy from dead organisms and organic waste products, allowing the material to be re-used and taking their own place in the food web of consumers. The bacteria that cause meat to rot are performing an important function; other examples are dung beetles, moths that eat animal fur, and on a larger scale, vultures that begin the breakdown of carrion.

A bio-inspired community of autonomous vehicles, needs a variety of "species," or elements of different designs performing a range of functions. In the case of Mars surface exploration, example units may be autonomous aerial vehicles, wheeled rovers, stationary or onboard processors, portable sensors, or orbiting satellites.

In nature, sustainable communities result from individuals of the member species performing their particular self-interested functions, such as seeking food, shelter, and water, or the establishment of territories and mating relationships. Individual plants, animals, and fungi are not motivated to maintain community balance. Rather, they have co-evolved to perform intricately related and complementary functions. In typical software control of multiple agents, each unit places at least partial value on the state of the overall system in determining its own actions. The holarchical approach intends to achieve balance in its member functions, without including system state in the onboard programming.

The description of a biological community is based primarily on the flow of energy. For a bio-inspired community of autonomous vehicles we take an analogy of energy and information. The gathering of information may be regarded as the motivating purpose for sending autonomous vehicles to Mars. The role of information producer can be filled by instruments and probes which collect information directly from the planetary surface or atmosphere. Information consumers take data from producers for processing and may release information in a different form to other information consumers. Figure 2 illustrates a simple information community.

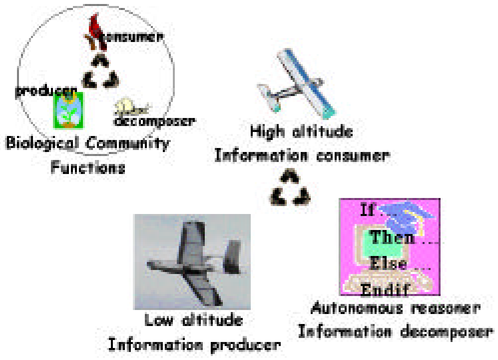

Figure 2. Information Cycle

Multiple information processing roles may be implemented onboard the same hardware platform. The steps in the information "food chain" show a similarity to the layers of abstraction familiar in robotic software. The decomposer role is less distinct with information than with natural material and energy. However, as data provide information and the collected body of information matures into knowledge, there must be a point in the cycle where the decision occurs that a goal is met and reinitialization of the collection processes can take place. Researchers on Earth may be the ultimate information decomposers about the Martian surface.

The Sub-robot Holarchy

Vehicle hardware subsystems may be likened to the organ systems of living things that provide functions such as structural support, locomotion, sensory input, and others. In hardware design, as in evolution, form follows function. The hardware in the BEES for Mars project uses established aircraft designs with no specific attempt to model the natural world. In software, however, a new approach to the control function of the autonomous vehicle is presented in the emotion-based approach.

4. EMOTIONAL SYSTEMS

Research into emotion-based systems is not a new field of study; previous work demonstrated the feasibility of emotional control for higher-level cognition and decision-making, typically geared towards social emotional behavior and mimicking human responses. Modeling an emotional nervous system for aspects of vehicle behavior and control beyond social aspects, however, is an approach whose utility and implementation feasibility remain to be demonstrated.

Unfortunately, the term 'emotion' is laden with many different preconceptions and prejudices. Historically, emotions have been characterized as high level cognitive states, as is typically seen in theoretical models in psychology. Such states are often arrived at through highly complex interactions that are difficult to model and which results in erratic human behavior. Many have suggested that emotions are an unfortunate heritage from animal ancestors which interferes with rational cognition, leading to such unequivocal statements as "robots should not be equipped with emotions" [20]. In this mindset, the complex mechanisms of emotion are considered distinct from and competing with cognition, especially reason and rationality.

Recent research activity and advances in the field of neuroscience has begun a radical transition in the way scientists are thinking about emotions. Recent findings suggest that emotions are a low level conduit for cognition, rather than a high level state that is distinct from cognition. Emotions provide the mechanism for rational cognitive decision-making and adaptive behavior especially significant in uncertain and complex environments. This mechanism is fundamental to all facets of animal behavior, from low-level instinctual and reflexive action to high-level decision making [15-17].

This project attempts to capture the mechanism of emotion that provides biological organism's adaptive behavior and rational cognitive decision making in uncertain and complex environments towards achieving goals. Emotion in the context of this paper does not refer to high level human emotions such as 'happiness' and 'sadness', which are superfluous and probably counter-productive to applications in UAV control and robotics in general. Rather, this paper presents an outline for a machine-based emotional nervous system to control all aspects of the autonomous UAV's behavior, from high level decision making to low level reflexive behavior, modeled after the emotional system of biological organisms.

Rationale and Goals of this Project

The motivation for the use of emotions in a goal-oriented system rests on three arguments. First, there are benefits to deriving inspiration from biological systems. Second, emotions play a large role in the adaptive behaviors demonstrated by animals and humans. Third, emotions are fundamental to the ability of humans in adapting to uncertainties when pursuing a goal. In defense of these statements is recognition that nature through evolution has had a very long period of time to optimize and refine biological designs, and has had time to expunge less desirable and detrimental aspects from its systems.

If emotions are considered a hindrance to goal-related tasks, or if they are not believed to provide adaptive benefits, then the question of implementation for goal oriented systems becomes academic. However, there is a growing amount of research that supports the use of emotion-based reasoning. Many argue that emotions are intimately linked with cognition and perception in general, for instance Picard in [14] states that a "critical part of our ability to perceive is not logical, but emotional". Emotions are essential to the adaptive qualities of human decision-making, and are the foundation of a rational mind [15][16]. Ventura et al. [17][21] point out the trend in current thinking is transitioning: from past consideration of emotions as an undesirable side effect carried over from our animal ancestors, to current beliefs that emotions are a powerful weapon to allow quick decision making in complex environments.

Despite the fact that many disparate models for emotional simulation have successfully been implemented, there is general recognition that biological components and mechanisms that evoke emotional reactions in animals to environmental and cognitive stimuli are not well understood [16]. Further, current capabilities of computers to process data might still be well short of that necessary to simulate such a complete model. The best approaches adapt theoretical models of emotion, capturing or simulating specific classifications from those models that emulate the expected behavior demonstrated by emotional organisms. For these categorizations, researchers have drawn inspiration from varying fields such as neuroscience, physiology, psychology, and philosophy [17]-[27].

The development of an emotion-based system requires formalization of a consistent model for emotions that is practical and machine-implementable. The researcher must appreciate the fundamental shortcomings of this endeavor; the characterizations will yield a functional description of the emotional system, defining and assigning quantifiable values to a complex system that is notoriously hard to define and near impossible to quantify. This intractability makes broad categorical argument on the utility of emotion based systems difficult; variant and often conflicting classifications, definitions, and implementations yield fundamentally different results, and aspects of one approach will not necessary be reflected in another.

The goal of developing a bio-inspired control system for the BEES for Mars project is two-fold. First, demonstrate a complete emotional model for control of the behavioral and decision making processes of an intelligent autonomous aerial vehicle with a mission of search and exploration in a remote environment. Second, demonstrate the advantage that emotions give a system for adaptive cognitive decision making over a non-emotional counterpart.

These goals emphatically exclude the development of an explorer system with human-mimicking interfaces, making a machine that thinks like a human, or making the explorer human-like in appearance or behavior. Rather, successful completion of this project will demonstrate a pragmatic implementation of a rational emotional nervous system that is simple, elegant, mathematically consistent, and that demonstrates rational and adaptive decision-making capabilities to overcome uncertainty, with eventualities that quantifiably outperform an unemotional counterpart towards accomplishing the same goals and objectives. This project will illustrate the trend to perceive emotions not as an undesirable component of biological cognition that hinders and interferes with rational thought processes, but rather as a fundamental component of rational decision making that provides a mechanism for sound deductive reasoning as well as prudent reflexive actions, in the hopes of providing greater flexibility for machine intelligence.

Related Work in Emotional Systems

There have been numerous initiatives to add emotional cognition to systems. The entertainment industry has used emotional models to provide human like behavior for characters in video games [28]. The OZ project at CMU [23] utilized an emotional model to provide human like behavior for interactive fiction and drama. Their approach adds a higher-level emotion based cognitive layer (the Em module) above an unemotional lower level to close the perceive-think-react loop. This model is loosely based on cognitive models of humans described in [25]. Ventura [21] contrasts this approach of placing a high level emotional layer above a lower level unemotional layer with a functional approach that is constructed emotion-based throughout. An example of this approach is given in [24], where a society of 'emotion proto-specialist' agents, each associated with a particular emotion, contributes to the emergent emotional behavior in a particular way.

In [17], a two-layered system is presented based on aspects from several theories on human cognition, including the Canon-Bard theory and Papez circuit theory [16]; the system has two layers for processing stimuli input: a slower cognitive processor which extracts cognitive features of the stimulus to form a generalized image model (for instance, the image of a zebra can be evaluated as an animal with four legs attached to a body, stripped coloring, etc.), and a perceptual processor for more basic and immediate instincts that produce a vector of desirability (e.g., a lion's perception of a zebra triggering its predatory instincts). The generalized image model is a database of information that might be rich, structured, divisible, and complex. The vector of desirability contains information that is simple, indivisible, and implemented as an ordered list of values relating to certain characterizations of the object, such as is it positive or negative, desirable or avoidable, edible or inedible, etc. The dual representations are used for reasoning purposes, where fast reasoning or reflexive actions can use the desirability vector, while slower cognition can access the generalized image model. A set of complementary mechanisms use data from one model to adjust the other.

McCauley in [22] presents a system based on the psychological theory called 'pandemonium theory'[26][27]. In this system, each emotion is represented by an agent called a codelet. The analogy of an arena is used, with stands, a playing field, and sub-arena. A multitude of codelets populate the arena. Codelets on the playing field are active, doing whatever they were designed to do, while codelets in the stand watch the activities of the codelets on the playing field, waiting for something to excite them. The level of excitation of a codelet in the stand is associated with how loud the codelets yell, which also excites other codelets. When excited to a certain level, a codelet will activate and move to the playing field to perform its action, which will in turn excite other codelets in the stands. Codelet actions are linked to other codelets with certain gains like links in a neural network. When entering the playing field, the sub-arena creates input and output associations between the entering codelet and the currently active codelets. This sub-arena performs the actual input and output functions of the system. The current goal context of the system emerges from the active codelets on the playing field. High-level concept codelets may remain on the playing field for quite a long time, influencing the actions of the whole agent for that time. Multiple goal contexts might be competing or cooperating to accomplish their tasks.

An Emotional Architecture for Agent Holons

The system we propose is fundamentally a functional emotional system according to the classification set forth in [21]. Our approach is based on several different theories, utilizing their strengths for different aspects of vehicle control. Higher-level cognition will be based on psychological theory of pandemonium [22][26][27], while reflexive actions will utilize the dualistic model of the Canon-Bard theory. These approaches are combined into a three layered control system: a low-level, time critical reflexive control layer, a mid-level control layer that commands the reflexive layer (similar to the way an autopilot commands the lower level automatic flight controls), and a high level cognitive decision layer.

In implementation, the software is composed of five components. A perceptual component provides interaction with the outside world. Second, an analytical component provides mathematical reasoning. The third component is a cognitive component to provide emotion based reasoning. A fourth reflexive component provides low-level flight and system control. The last component is an output component to allow the system to interact with the environment.

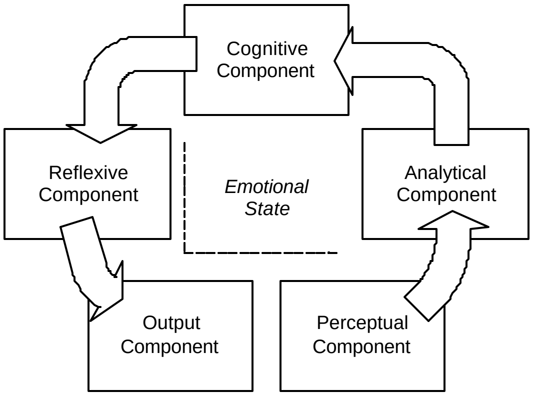

Figure 3. Components of the Architecture.

The components of the system are shown in Figure 3 above. Note that the arrows represent overall data flow to illustrate the circular nature of the data and to illustrate the highest-level perceive-think-act loop. Other loops exist in this system for the different layers of control; for instance, the perceptual-reflexive-output components form the tight inner loop for control. These loops will be discussed in more detail in the following sections.

Perceptual Component

The perceptual component introduces data into the system from the external world, or from internal sensors monitoring the health and state of the system. Data include measurements from sensors, such as accelerometers, thermometers, and GPS, communications with other agents or operators through network interfaces or other communication hardware, and internal software state parameters describing the health of the system. Processing may be more or less complex, depending on the input and the emotional state of the system. Video images, for instance, may be processed by the perceptual components to determine signals that are passed to the rest of the system. The amount of processing and the availability of data depend on the emotional state of the system. Excitation of particular desires and anxieties will adjust the relative priorities for processing certain components, and can adjust their parameters to magnify their effect in the overall system.

Analytical Component

The analytical component, as its name suggests, performs most of the computational analysis required to drive the emotions of the system. The high level emotional state of the system will direct which computations need to be performed in order to satiate the cognitive component's need for information, which in turn satiates current anxieties and provides input for decision making. This component will consume the output from the perceptual component to perform its computation, taking part in the highest-level data loop. For instance, as an explorer ventures farther from an origin point, the anxiety of safely returning will increase, prompting the analytical component to calculate the amount of fuel required to safely return. This input will further excite or relax the emotional anxiety, prompting an adjustment of the search vector to reduce the time rate of change of the distance from the origin point, or triggering an emotional state transition to reflect the fact that all search activities should cease and the explorer should return to its origin point.

Cognitive Component

The cognitive component performs the high level reasoning and decision making needed to achieve high level goals. The implementation of this component is based on the psychological theory of pandemonium, although modified from the earlier adaptation by Jackson [27] from the basic theory of Selfridge [26]. The basic agents in the system (the demons or codelets) represent machine anxieties, which operate in the same arena analogy of the basic pandemonium model. Anxieties will be excited from the results of analytical calculations performed, from perceptual outputs, and from other related anxieties. The anxieties that have reached a certain excitation level (and are on the playing field) determine the emotional state of the system, which will be used to determine the explorer's state from a predefined fuzzy modality. Anxieties, however, do not have actions directly associated with them as in the Jackson and McCauley adaptation, but rather have an 'analog' effect on the desires of the explorer depending on excitation level of associated anxieties, which in turn affect behavior. For instance, the 'need to return home' anxiety can cause several behavioral modifications to occur, from modification to search vectors to a complete state change when sufficiently excited.

The cognitive component selects and adjusts its course of action from its internal emotional state, and its main function will be to adjust the reflexive component to effect action. The cognitive component will also adjust the analytical and perceptual components, directing them to provide computations and modify input based on its current anxieties.

Reflexive Component

The reflexive component of the system uses the emotional state of the system and commands from the cognitive component to implement control of the explorer. For UAV, this component implements the automatic flight controls of traditional aerial systems. The reflexive component forms a tight control loop with the perceptual-reflexive-output components, performing time critical control. The processing of the reflexive component is minimal.

The reflexive component of the system is based on the dualistic neuroscientific theories of Canon-Bard theory and the Papez circuit theory. The dualistic model provides fast real-time controls based on a vector of desirability, which is analogous to the gains in a conventional flight controller. However, we adapt the dualistic model for continuous analog input. The input comprises of input from GPS, accelerometers, pressure inducers, and other sensors needed to stabilize and control flight. This data will be fed directly through a feedback loop whose gains are determined by the desirability vector, as in a typical feedback controlled flight system. This data model will also be fed into a generalized model of the data, which will accumulate and analyze data with help from the analytical component of the system. This dual representation of input (the continuous analog input from the sensors) will feed into the output for fast reflexive control, and will also feed into specific emotional anxieties in the cognitive model that deal with controlling the system, forming a higher level control loop between the perceptual-reflexive-cognitive components.

Three Layered Control System

Emergent from the design of this system is a three-layered flight control system: the reflexive layer, the guidance layer, and the cognitive layer. The reflexive layer performs the time critical, real-time control needed to stabilize and control the UAV. The mechanism that enables this functionality is the fast-acting desirability vector from the dualistic Canon-Bard model, implemented in the tight loop formed from the perceptual-reflexive-output components. This loop implements automatic stability and control of the aircraft though manipulation of the control surfaces. Several desirability vectors are maintained by the reflexive system, which will transition from one set to the next based on the emotional state of the guidance control layer. The desirability vector can be directly modified by the guidance layer through a process referred to as marking, and likewise can adjust the guidance layer through a process called indexing. Constant adjustments to the emotional states through marking and indexing provide a mechanism to enable adaptive and learning behavior for the control systems in accomplishing its desires and goals.

The guidance layer of the control system encompasses the generalized image model, the dual of the desirability vector representation of stimuli from the Canon-Bard model. Since the generalized image model is a richer and more complex set of observations and descriptions of the stimuli, its complexity requires a more elaborate storage scheme and slower access to data. This model is sufficient for the less time-critical guidance loop, which will perform monitoring and correction of the desirability vector. Part of this middle layer will also function analogous to a modal autopilot layer, as well as performing task oriented data monitoring and evaluation through an arena based emotional model. The processed data from the generalized model will feed into control-specific anxieties that will in turn mark and manipulate the desirability vectors to close the loop.

The cognitive layer has less timing restrictions than either of the two lower layers, and performs the higher level reasoning and decision making for the system. The mechanism to support reasoning is adapted from the theory of pandemonium. The output of this layer provides the high level goals for the system, which may include self preservation, long range exploration, and target identification. The pandemonium arena will be shared between the cognitive and guidance layers, with each layer populating the system with codelets for specific purposes. Much of the challenge in adapting the arena analogy towards flight control will lie in establishing codelet definitions, defining how they interact with each other in a network, and defining a mechanism for establishing the gains between each codelet.

Towards an Emotional Holon

Our approach will differ from the majority of previous initiatives at introducing emotions into computational systems; where as previous approaches have largely either been geared towards functions such as mimicking human social behavior in computer and machine interfaces or have been subjugated to the very highest level reasoning component, this project will strive to introduce emotions to an intelligent system for its adaptive and reasoning capabilities in a manner which emotions are fundamental to operation of all behaviors exhibited, from low level automatic control of the agent to high level decision making. Further, the system is intended to be scalable from individual agents to a communal holarchy of such agents, interacting in complex and adaptive manners to achieve an overall goal. The eventual goal for interactive communities is to demonstrate adaptive emergent behaviors that will help the community thrive in the face of unforeseen causality, uncertainty, and catastrophe. The initial stage of this endeavor will be to demonstrate the utility of emotional systems for single agent UAVs, while demonstrating its potential applicability to the larger agent holarchy.

5. APPLICATION TO UNMANNED AERIAL VEHICLES

Implementation Challenges

There are several reasons for the interest in developing a holarchical approach to the design of autonomous systems and applying emotional models to decision-making and control. One challenge is how to develop modules and groups of modules that will scale well, both within a single aircraft, or across multiple aircraft or ground processors. A holarchical approach may provide insight into how modules, data, and actions are managed in such designs.

Another challenge is in how to structure the resources in a multi-aircraft mission. As alluded to earlier in this paper, much of the research in regards to multi-agent behavior has been on swarms or swarming behavior. It is strongly believed that what is actually needed is a heterogeneous approach, where multiple aircraft and ground processors must work together, applying different sensors, functions and skill sets to solve a problem. A holarchical approach, where aircraft can cooperate with each other on multiple levels is the best way to accomplish this goal.

A third challenge is in how to more effectively inject behavioral concepts to the programming of the autonomous system. Our application of an emotional paradigm to the reasoning and control of the aircraft or multi-aircraft group should allow us to examine how it would be developed based on behavioral, rather than conventional programming methods. In contrast with standard programming of if-then else constructs, the behavior of the aircraft will be defined by the interaction between modules and systems of modules. These interactions may be learned via training and experience.

Example Mission Scenarios

To illustrate how these new technologies would be applied, the following mission scenario is offered. Two aircraft are sent out to image an area, looking for the existence of a specific type of mineral or rock. One aircraft is a scout, with long endurance and sufficient, but limited sensing capability. The other aircraft has a more elaborate sensing capability that weighs more and therefore reduces its range or time on station. A ground processing system is also available that can take data from the scout or other aircraft and process it in real time to provide addition information with which to make decisions. A higher level of imaging capability can be applied when both aircraft work together and pass their data through the ground system.

In this example, both aircraft could search separate areas in search of the specific mineral. Each aircraft would be responsible for maintaining its own safety and resources in flight, and also the schedule for the area in which it was searching. When either aircraft sensed the mineral, the data could be downloaded to the ground system for further processing while the aircraft continued to search. A decision to reposition the heavily-sensored aircraft to further sense a rock found by the scout would depend on multiple resource constraints that would have to be resolved individually and collectively: (positive identification of the rock sample, position of the aircraft and their search schedules, fuel, and other constraints). The cooperation and deliberateness of the holarchical approach is in contrast with a swarm-type process which is comparatively more chaotic and inefficient in nature.

The mission described above could be developed using a standard programming approach. The decision making, cooperation, and actions of the individual entities could also be implemented using an emotional model. The goals and subgoals of each aircraft and its internal modules could be modeled as anxieties that would drive it to make certain decisions and actions. For example, although the scout aircraft could have reported that it found the specified rock, and the ground processor may have verified this finding (indicating the desire to stereo image that site), the more heavily sensored aircraft may have short-term resource or schedule issues that had a higher anxiety level at that time. In the case of behavioral–based designs, although not straightforward, it may be easier to train systems to work together than to program the individual intelligent systems and the mission as a whole.

System development

We are currently working to add an additional processor and sensor capabilities to our target platform to support additional onboard reasoning to support holarchical and emotion-based approaches.

In parallel with this effort, a hardware-in-the-loop simulation capability is being developed, allowing demonstration and testing of algorithms and software in advance of flight-test. This software will be enhanced to support real time simulation of sensor data to the aircraft while in flight, providing the capability to simulate environments and sensor inputs that may be quite different from the airport or location in which the aircraft is being flown. These virtual capabilities will also aid the development and testing of multi-agent behavioral concepts before additional platforms are available.

Upcoming work will enhance the processing and communication and capabilities of our ground station. These improvements will allow the ground station to exchange data and information with more than one aerial asset. As a steppingstone to multiple UAV autonomy, we will add a second aerial vehicle to our system that will be used initially in a non-autonomous mode to test the operations of the ground system with the other aerial vehicle.

Mission Development

We will use the above capabilities to first develop holarchical mission designs and then add emotional models to the individual agents that will move us toward being able to support increasingly complicated mission scenarios.

We will initially focus on developing a mission holarchy between the ground and intelligent aerial vehicle. This should shed light on the operations and interactions needed between these differing components. We will then expand the mission design to include a second aerial vehicle. We will use this design to understand how the holarchy can be enhanced to include assets that are similar in operation but are heterogeneous in capabilities and objectives.

In parallel, we will strive to develop an emotional control model within a single aerial vehicle with the goal of a simple scenario based on recognizing an image and acting in response. This basic scenario will involve developing the core emotion software, and then deriving and implementing the low and high level emotions and control vectors. One of the outputs of the development will be an evaluation and comparison of emotional vs. conventional control models for achieving similar tasks.

With a firm understanding of emotional control models, we will then work to add an aerial vehicle with this control system to an existing mission holarchy. This will involve translating the communication and interaction models developed for the hierarchy into emotional control equivalents. With success, we will expand this development to include other agents in the holarchy, taking in consideration the differences between their motivations and function in the mission.

A long-term goal of this effort is to be able to easily define and achieve complex missions through assembly, first by defining a mission holarchy that includes goals and resources. Then by adding emotional agents as those resources that can decompose the requirements and act within the hierarchy based on prior experience with similar work.

6. SUMMARY

In summary, the notion of a holarchy and how this concept could be applied to the design of multi-level, heterogeneous intelligent systems that work together to solve challenging mission objectives has been described. The definition and application of the emotional holon concept has been described, as well as how it could be constructed within a holarchy and used to control the decision-making and actions of a robotic system.

It was also discussed how holarchical concepts and emotional decision-making and control could be applied in an example mission scenario. Finally, our near term development of hardware and software platforms required to support this inquiry was described along with a plan for the realization of increasing capabilities of holarchy-based missions using emotional agents.

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8. REFERENCES

[1] Thakoor, S., et al, "Bioinspired Engineering of Exploration Systems for NASA and DoD," **Artificial Life VIII: 8th International Conference on the Simulation and Synthesis of Living Systems**, Sydney, Australia, December 9-13, 2002.

[2] Gundlach, J.F., "Unmanned Solar-Powered Hybrid Airships for Mars Exploration," **AIAA 99-0896, 37th AIAA Aerospace Sciences Meeting and Exhibit**, Reno, NV, January 11-14, 1999.

[3] Jones, J. "Inflatable Robotics for Planetary Applications," *Proceedings of the 6th* **National Symposium on Artificial Intelligence and Robotics & Automation in Space: I SAIRAS 2001**, Canadian Space Agency, St-Hubert, and Quebec, Canada, June 18-22, 2001.

[4] Young, L.A., Chen, R.T.N., Aiken, E.W., and Briggs, G.A., "Design Opportunities and Challenges in the Development of Vertical Lift Planetary Aerial Vehicles," **American Helicopter Society (AHS) Vertical Lift Aircraft Design Conference**, San Francisco, CA, January 2000.

[5] Young, L.A., Aiken, E.W., Derby, M.R., Demblewski, R., and Navarrete, J., "Experimental Investigation and Demonstration of Rotary-Wing Technologies for Flight in the Atmosphere of Mars," **58th Annual Forum of the American Helicopter Society**, Montreal, Canada, June 11-13, 2002.

[6] Young, L.A., Aiken, E.W., Briggs, G.A., Gulick, V., and Mancinelli, R., "Rotorcraft as Mars Scouts," **IEEE Aerospace Conference**, Big Sky, MT, March 2002.

[7] Young, L.A., Briggs, G.A., Derby, M.R., and Aiken, E.W., "Use of Vertical Lift Planetary Aerial Vehicles for the Exploration of Mars," **NASA Headquarters and Lunar and Planetary Institute Workshop on Mars Exploration Concepts**, LPI Contribution # 1062, Houston, TX, July 2000.

[8] Clarke, V.C., Jr. "The Ad Hoc Mars Airplane Science Working Group," **NASA CR-158000**, November 1978.

[9] Girerd, A.R., "The Case for a Robotic Martian Airship," **AIAA 97-1460**, 1997.

[10] Datta, A, Roget, B., Griffiths, D., Pugliese, G., Sitaraman, J., Bao, J., Liu, L., and Gamard, O., "Design of the Martian Autonomous Rotary-Wing Vehicle," **AHS Specialist Meeting on Aerodynamics, Acoustics, and Test and Evaluation**, San Francisco, CA, January 2002.

[11] Huntsberger, T., and Rose, J., "BISMARC: A Biologically Inspired System for Map-Based Autonomous Rover Control," **Neural Networks Journal**, Vol. 11 (1998), Pergamon Press, pgs. 1497-1510.

[12] Kaneshige, J., and Gundy-Burlet, K. "Integrated Neural Flight and Control System," **AIAA**, 2001

[13] Sugawara, K. and Watanabe, T., "Swarming Robots - Foraging Behavior of Simple Multi-robot System," **Proc. of the IEEE/RSJ Intl. Conf. On Intelligent Robots and Systems**, pp. 2702-2707, 2002

[14] Picard, R. **Affective Computing**, Massachusetts: The MIT Press, 1997

[15] Damasio, A. R., **Descartes' Error: Emotion, Reason, and the Human Brain**, New York: Avon Books, 1994

[16] LeDoux, J. **The Emotional Brain**. New York: Simon and Schuster 1996

[17] Ventura, R., Custodio, L, and Pinto-Ferreira, C. "Artificial Emotions, Good Bye Mr. Spock!" In **Proceedings of the 2nd International Conference on Cognitive Science**, pages 938-941, Tokyo, Japan, 1999

[18] Plice, Pisanich, Young, Lau. "Biologically Inspired Behavioral Strategies for Autonomous Aerial Explorers on Mars", **In Proceedings of the 2003 IEEE Aerospace Conference**, Big Sky, MT, March, 2003

[19] Koestler, A. Janus: a summing up, New York: Random House, Inc., 1978.

[20] McCarthy, J. "Making robots conscious of their mental states." **Invited lecture at the Symposium on Consciousness**, AAAI, Spring 1995

[21] Ventura, R. and Pinto-Ferreira, C. 1998 "Emotion-Based Agents : Three approaches to implementation", in **Workshop on Emotion-Based Agent Architectures (EBAA'99)**, pages 121-129, May 1999

[22] McCauley, L and Franklin, S. "An Architecture for Emotion", **The Institute for Intelligent Systems**, University of Memphis.

[23] Reilly, S. and Bates, J. "Building Emotional Agents", **Technical Report CMU-CS-92-143**. CMU School of Computer Science, Carnegie Mellon University, May 1992

[24] Valesquez, J. "Modeling Emotions and Other Motivations in Synthetic Agents", In Dolores Canamero, editor, **Emotional and Intelligent: The Tangled Knot of Cognition**, pages 164-169, 1998

[25] Ortony, A., Clore, G., and Collins, A., **The Cognitive Structure of Emotions**. Cambridge, UK: Cambridge University Press, 1988

[26] Selfridge, O. 1959 "Pandemonium: A Paradigm for Learning", **In Proceedings of the Symposium on Mechanisation of Thought Process**. National Physics Laboratory.

[27] Jackson, J, "Idea for a Mind", **SIGART Newsletter**, no 181 (July):23-26 1987

[28] Pisanich, G., Prevost, M "Representing Human Characters in Interactive Games" **In Proceedings of the Computer Games Developer's Conference**, San Francisco, Miller-Freeman, Inc, 1996