AUTONOMOUS CONTROL SYSTEMS – Applications to Remote Sensing and Image Processing

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ABSTRACT

One of the main challenges of any control (or image processing) paradigm is being able to handle complex systems under unforeseen uncertainties. A system may be called complex here if its dimension (order) is too high and its model (if available) is nonlinear, interconnected, and information on the system is uncertain such that classical techniques cannot easily handle the problem. Examples of complex systems are power networks, space robotic colonies, national air traffic control system, an integrated manufacturing plant, the Hubble Telescope, the International Space Station, etc. *Soft computing*, a consortia of methodologies such as fuzzy logic, neuro-computing, genetic algorithms and genetic programming, has proven to be powerful tools for adding *autonomy* and *semi-autonomy* to many complex systems. For such systems the size of soft computing control architecture will be nearly infinite. In this paper new paradigms using soft computing approaches are utilized to design *autonomous* controllers and *image enhancers* for a number of application areas. These applications are satellite array formations for synthetic aperture radar interferometry (InSAR) and enhancement of analog and digital images.

1. INTRODUCTION

For the past 50 years, extensive progress has been achieved in our understanding of how to model, identify, represent, measure, control, and implement digital controllers and image enhancers for complex systems. However, to design systems having high MIQ® (Machine Intelligence Quotient, registered trademark of Lotfi A. Zadeh), a profound change in the orientation of control and image processing theories may be required.

Currently, one of the more active members of soft computing paradigms is *fuzzy logic*, a logic of human approximate reasoning and set with unsharp boundaries. Two of the more popular applications of fuzzy logic are *fuzzy adaptive optics control* and *fuzzy image processing*. Fuzzy controllers (or image enhancers) are expert systems that smoothly interpolate between knowledge-based rules. Rules fire simultaneously to continuous degrees or strengths and the multiple resultant actions are combined into an interpolated result. Processing of uncertain information and saving of energy using common sense rules and natural language statements are the basis for fuzzy expert systems. The use of sensor data in practical systems involves several tasks that are usually done by a human in the decision loop; e.g., an astronaut adjusting the position of a satellite or putting it in the proper orbit and a driver adjusting a vehicle's air-conditioning unit. All such tasks must be performed based on the evaluation of data according to a set of rules in which the human expert has learned from experience or training. Often, these rules are not crisp, i.e., some decisions are based on common sense or personal judgment. Such problems can be addressed by a set of fuzzy variables and rules which, if properly constructed, can make decisions that are comparable to those of a human expert. In fuzzy image processing, the uncertainties such as aberrations of images or unclear pixel-level information can be handled through expert knowledge stemming from the foundation of fuzzy IF-THEN rules.

This paper presents two applications of soft computing approaches to complex systems - a multi-satellite Synthetic Aperture Radar Interferometry (InSAR) within the realm of satellite arrays of formation flying as well as an application of image enhancement through fuzzy logic. The structure of the paper is as follows: Section 2 briefly describes autonomy through soft computing. Section 3 introduces an InSAR Satellite Array system, which utilizes both the optimal control theory and a multi-objective genetic algorithm for deployment and recovery of micro-satellites in formation flying format. Section 4 presents a fuzzy expert system for analog and digital image enhancement. A summary is given in Section 5.

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2. AUTONOMY THROUGH SOFT COMPUTING

As mentioned earlier, soft Computing is an umbrella terminology used to refer to a collection of intelligent approaches such as neural networks (NN), fuzzy logic (FL), genetic algorithms (GA), genetic programming (GP) and neuro computing. Soft computing techniques allow one to design autonomous expert systems through learning (NN), optimization (GA) or reasoning (FL).

Neural networks, genetic algorithms and genetic programming are augmented with fuzzy logic-based schemes to enhance artificial intelligence of automated systems. Such hybrid combinations exhibit added reasoning, adaptation and learning ability. One can utilize various combinations of these approaches to design expert systems fro control, image processing or remote sensing. Some of the applications of these hybrid approaches have been hierarchical NN-fuzzy controller applied to a direct-drive motor, a GA-fuzzy hierarchical controller applied to position control of a flexible robot link, and a GP-fuzzy behavior based controller applied to a mobile robot navigation task cooperative robotic systems such as the soccer robots, satellite arrays, image enhancement, water purification, etc. [de Silva book]. The NN-fuzzy architecture takes advantage of NN for handling complex data patterns, the GA-fuzzy architecture utilizes the ability of GA to optimize parameters of membership functions for improved system response, and the GP-fuzzy architecture utilizes the symbolic manipulation capability of GP to evolve fuzzy rule-sets.

3. OPTIMAL AUTONOMOUS DEPLOYMENT OF A SPACECRAFT ARRAY

This proposed research [1] has the primary objective of demonstrating autonomous control for optimally configuring a remote sensing spacecraft array fitted with Synthetic Aperture Radar (SAR) sensors. Figure 1 depicts the array which consists of a mothership and three micro-satellites (probes under 100 Kg) Here, it is assumed the mothership spacecraft carrying multiple deployable SAR equipped probes is launched on a solar system exploration mission. The probes are deployed into an array structure to perform single pass SAR Interferometry (*InSAR*). With three spacecraft, three simultaneous interferometric images of a target can be combined into a composite image. Subsequently, the probes are recovered once the observation is complete.

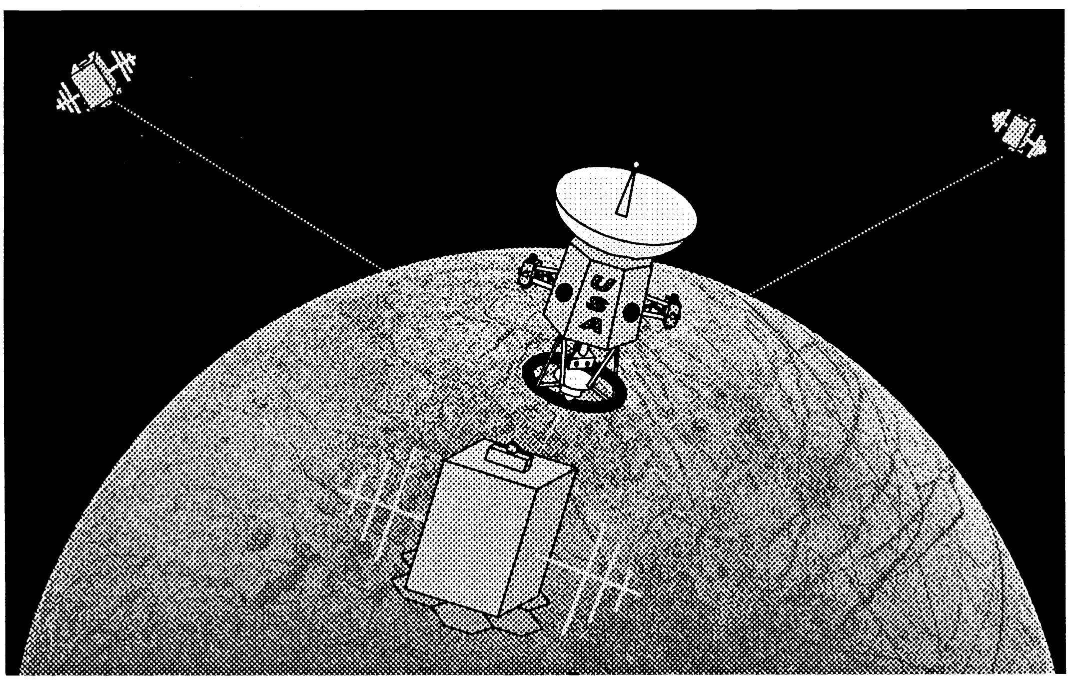

Figure 1. Depiction of the remote sensing array near Jupiter's moon Europa.

Autonomous array configuration is defined as the spaceborne system optimally computing and configuring the array formation given observation goals by mission controllers. For this research, autonomous control will be developed within a hierarchical structure distributed among the mothership and three sensor probes. The mothership coordinator will autonomously perform multiobjective optimization to design an array structure that meets free-fall geometry goals during the specified observation interval while keeping within spacecraft deployment and recovery constraints. The probes, in turn, will individually and autonomously perform fuel-optimal maneuvers to meet the coordinator's array structure specification. During maneuvering, each probe will use state feedback to re-compute its thrust profile to compensate for unmodeled disturbances, keep fuel-to-go at a minimum, and guarantee reaching the specified state at the initial observation point.

This proposed research is expected to contribute to the spacecraft control community by providing practical methodologies for operating InSAR arrays that must configure themselves autonomously due to vast distances between the spaceborne system and mission control. Although the driving force to develop this technology originates from a desire to increase capabilities of exploring distant solar system planets, moons, asteroids, and comets, the technology may be used to automate Earth orbiting spacecraft arrays.

The proposed research will study array deployment and recovery for three mission scenarios. The first scenario is the *Hyperbolic Flyby* (Figure 2). In this scenario, the probes are stowed on the mothership as the system travels on a rendezvous trajectory to a planet, asteroid, or comet. With the region of interest on the surface of the target body known, the mothership designs the optimal probe formation for the flyby. In this work [1], it is shown that the probe release point, θ_o, is a variable in a formation design objective function within the framework of a multi-objective GA. The design process produces specified state vectors for each probe to reach by the time the mothership arrives at the initial observation point, θ_i. During the observation interval, the probes free-fall while their SAR sensors point to and observe the region of interest. If the design process was successful, the probe formation will meet InSAR performance objectives throughout the observation interval. When the mothership reaches θ_f, the observation concludes and the probes compute a minimal thrust trajectory back to the mothership.

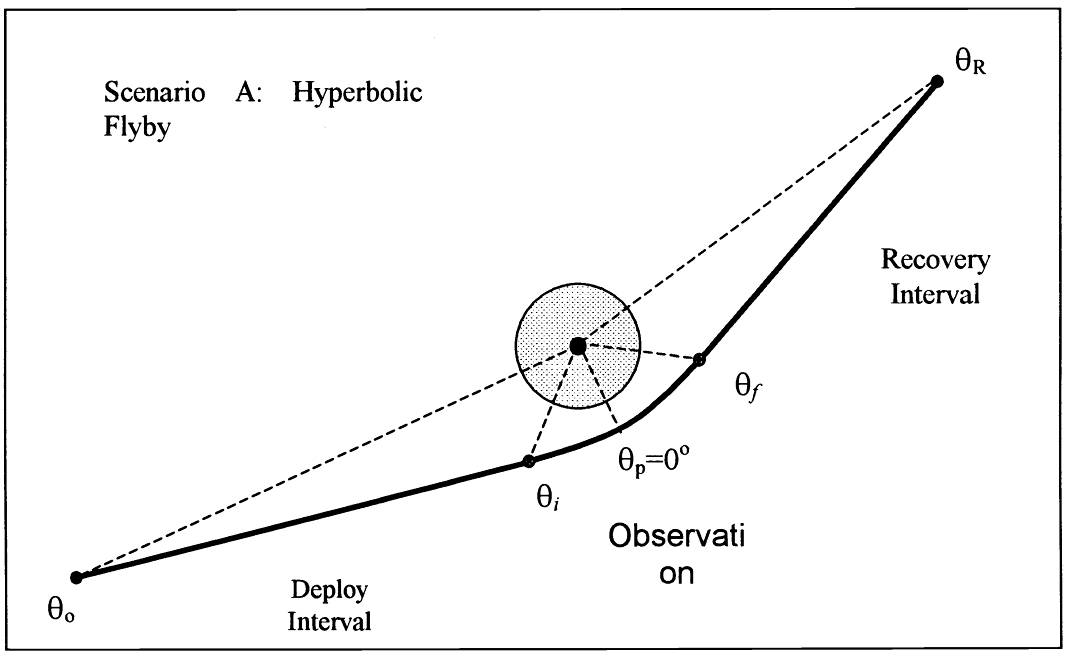

Figure 2. Hyperbolic Flyby. Probes are released from mothership at true anomaly θ_o. Probes are required to be at specified relative state when mothership reaches true anomaly θ_i. Probes free-fall while sensors point to and observe target region. Observation ends when mothership reaches true anomaly θ_f. Probes compute optimal trajectory and return to mothership for recovery.

The second scenario observation is also made from a hyperbolic flyby, but this time the flyby transitions from a large elliptical orbit. Similar to the Galileo tour of Jupiter's moons, the system would execute trim maneuvers to set up for the next moon flyby. Note that the probes would have to be stowed for any large system orbital adjustment. Also note that the probes have to compute their trajectory to and from the observation interval in two stages. The first stage needs an elliptical model, and the second stage a hyperbolic model. The model distinction is required by Carter's [2] optimal rendezvous methodology that the probes will use.

The third scenario may be used for long term encounters with distant planets or moons, or perhaps mapping or surveillance missions here at Earth. Once established in orbit, the system would design the formation to meet InSAR observation objectives for selected regions of interest. Once deployed, the formation may require trim maneuvers after several orbits. These could be done one probe spacecraft at a time for continued (though degraded) observation, or all at once if the mission allows the system to go offline for a short period of time. Large system trim maneuvers would require the probes be recovered and stowed prior to mothership maneuvering.
The current research is taking place at the ACE Center at the University of New Mexico and further results will be forthcoming.

4. AUTONOMOUS IMAGE ENHANCEMENT

4.1 Enhancement of Digital Images

SmartPhotoLab© is software designed to enhance the quality of digital images. An expert system embedded within SmartPhotoLab© detects undesired quantities and enhances the quality of the image. Unlike most of the commercial products on the market this software tool does not require the user to have any image processing knowledge. An image can be enhanced by a click of a button. SmartPhotoLab© is a user friendly, multi-document and menu driven software tool. The user has the capability to enhance the image in one shot, or go through the intermediate steps to visually see the process of enhancement. The inputs of the expert system are color, tint, brightness, and contrast. The outputs of the expert system are the new color, tint, brightness, and contrast that will result in an enhanced image. A flow chart of the software is presented in Figure 3. A typical enhancement for Internet-based images using SmartPhotoLab© is shown in Figure 4.

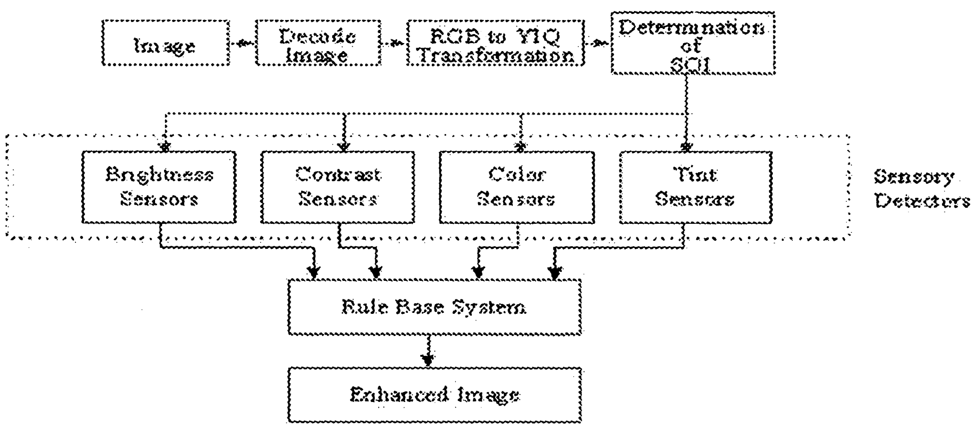

Figure 3: SmartPhotoLab© (flow chart).

4.2 Enhancement of Analog Images

The same concept is applied to analog images. An expert System was developed to obtain a good quality photo automatically without the need for a human expert. This application is briefly described in the following subsections. The experimental system is outlined and the steps of the application are given.

(a) (b)

Figure 4: Typical digital images for skin tone and image enhancement
(a) Image before enhancement, (b) Image after enhancement.

Color Photography Photographic films and paper (color) are manufactured with three separate light sensitive layers of emulsion, one is sensitive to red light, one to green light and one to blue light. Each of the layers, when exposed and processed, forms a specific color dye. The dyes are the complementary color of corresponding light sensitive layer. The overall density of the recreated color, that is how dark or light it appears, is dependent upon the densities of the dye layers in the film. The density of a dye layer is directly proportional to the exposure it receives. Consequently, by controlling the light using transparent filters as well as the exposure time, the quality of the image could be controlled.

The current systems require an expert to print the image and then based on the output, determine the required filtration of light and the exposure time to obtain a good quality photo. Figure 5 demonstrates the process of developing a color photo with a human expert. Generally, the operator selects a filter pack and exposure time, and then prints the photo. If the result is not satisfying, a different setting will be chosen. Consequently, the process of printing is time consuming and for non-experienced users is hard and expensive.

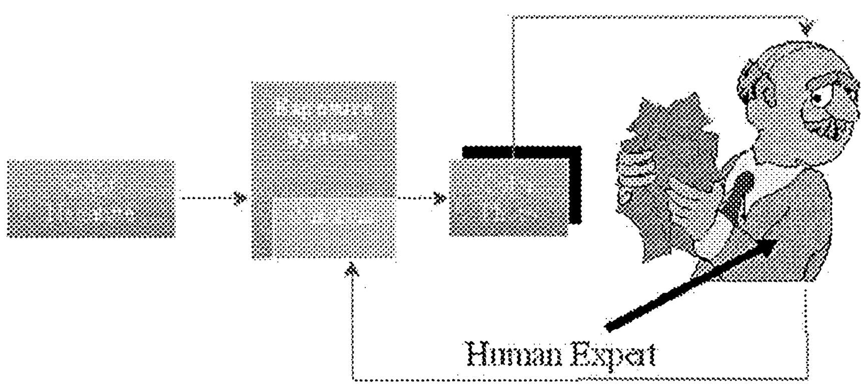

Figure 5: Exposure system controlled by a human expert.

Experimental Setup The hardware setup is shown in Figure 6. The image from the color negative is digitized and entered into the computer. The negative image is then transformed into a positive image (Figure 7). The positive image is then entered into SmartPhotoLab©. The attributes of the image are determined and used as an input to the expert system. The output of the expert system is the new cyan, magenta, and yellow filters and the exposure time necessary to obtain the final good quality image (see Figure 8). A typical analog image (35mm color photos) enhancement using the

SmartPhotoCard© process is shown in Figure 9. For further details on this patented [3] project interested readers may refer to the works of El-Osery, Jamshidi and associates [4-7].

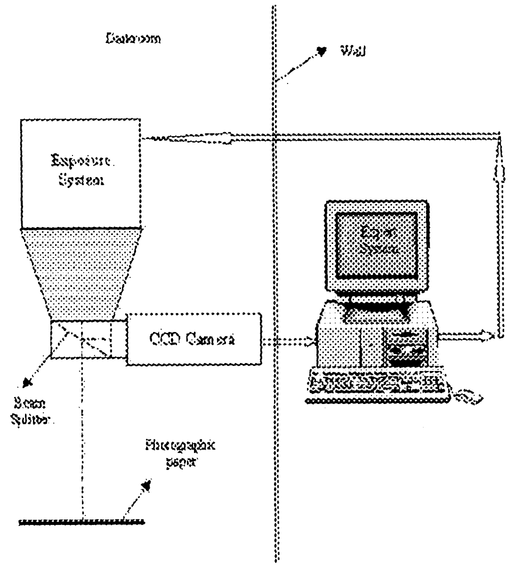

Figure 6: Hardware setup.

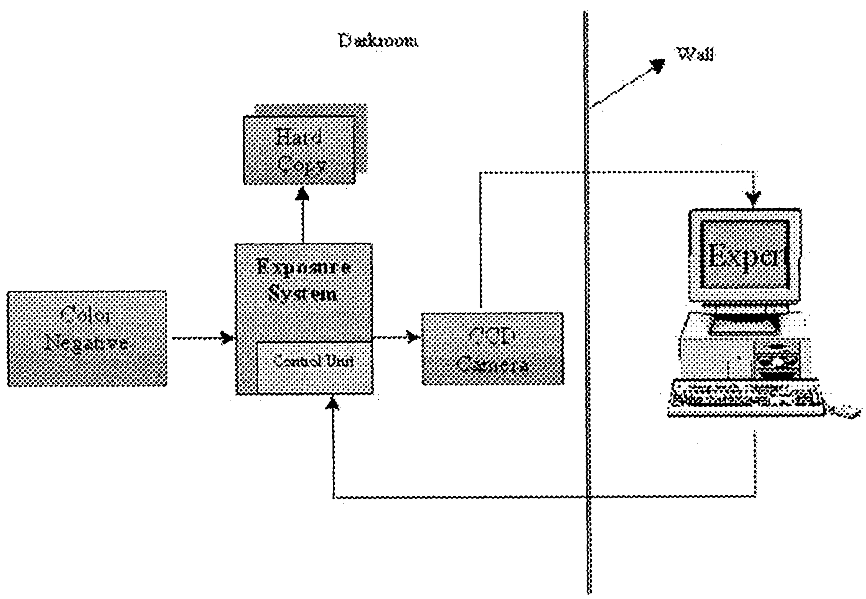

Figure 7: Automated process of enhancing an analog image.

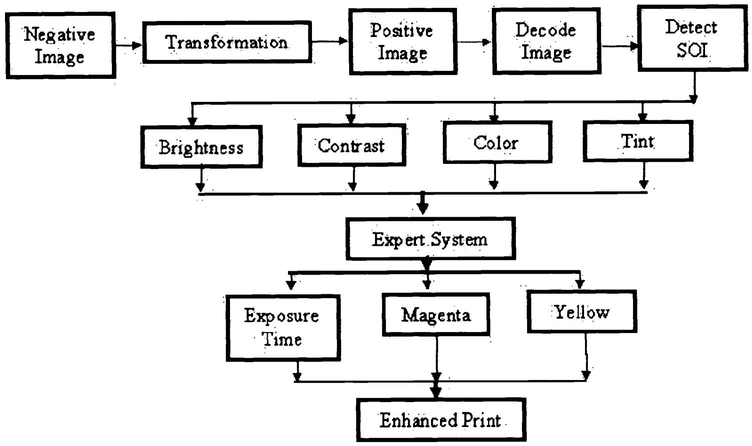

Figure 8: Software flow chart.

(a) (b)

Figure 9: Typical enhancement of analog images (a) Image before enhancement, (b) Image after enhancement.

5. SUMMARY AND CONCLUSIONS

The basic theme of this paper was *autonomy* through elements of soft computing. A number of robotic applications were used to illustrate these architectures. These autonomous controllers are simple to implement in a laboratory environment on either a PC or on a chip-level board. Soon, autonomous control through intelligent paradigms technology will be a matter of economy and not controversy. It features applications in a wide variety of fields such as control, pattern recognition, medicine, finance and marketing. These techniques should be given serious consideration as additional tools for the solution of problems that are suitable for this technology, notably, problems where a mathematical model is neither available nor feasible. Applications to complex systems require careful consideration of the system's model, its structure, the behavior and means of sensory data, and rule specialization and hierarchy. Finally, new avenues should be opened for new software design and analysis of control systems utilizing the power and efficiency of tools such as fuzzy logic, neural networks, and genetic algorithms. The expert systems (Section 5) designed for both analog and digital images have demonstrated very promising results. The results contribute to software and a hardware product that will automate the process of image enhancement in both analog and digital domains.

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