AFOSR Research Programs in Image Fusion

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Abstract - *The U.S. Air Force Office of Scientific Research supports basic research in image fusion within several programs. These programs are presented in context of Air Force technology needs for targeting, image exploitation, and autonomous systems. Programs include research involving human perception and neural processing in other biological systems, algorithms for fusion from multiple sources and platforms, and novel sensors. Available mechanisms for support of collaborative research will also be presented.*

Keywords: Sensors, Displays, Shape Encoding, Algorithms, Learning, Control.

1 Introduction

The Air Force Office of Scientific Research (AFOSR) is the single manager of basic research for the U.S. Air Force (USAF). Basic research is defined in the U.S. Defense Department as the most fundamental of work along a research and development spectrum from knowledge discovery to technology demonstration. The AFOSR supports many areas of science, but focuses its support on topics expected strongly to contribute to the technology needs of the USAF. These programs are executed largely through grants and contracts to industrial and academic researchers. Description of current topics of AFOSR support is available at the AFOSR home page (http://www.afosr.af.mil).

Fusion, the topic of this meeting, is not an AFOSR focus area because AFOSR defines topics in scientific terms, not technological ones. Nevertheless, several AFOSR programs contribute to fusion technologies. I will describe program contributions each in turn, emphasizing those that take advantage of biological signal processing, of special interest to me.

1.1 AFRL Fusion Science and Technology

AFOSR is a part of the Air Force Research Laboratory (AFRL) and uses its scientific programs to support technology developments within AFRL's several technology directorates. These technology directorates conduct some basic research, but have primary responsibilities for technology development and application. Some of the fusion-related work in the Sensors Directorate (SN) and the Information Directorate (IF) will be illustrated. For example, these two directorates of AFRL work together on a "fusion network" for technology demonstrations that integrate sensors and processing. AFOSR contributes to SN technology advances in novel sensors, modeling of the environment, data storage and processing. AFOSR also contributes to IF technology advances in data and information fusion and image exploitation.

Through the AFRL technology directorates, AFOSR funded science is grounded in applications of interest to the Air Force. In addition to SN and IF, other directorates of the AFRL contribute to fusion technologies. Some information on the work of each of the technology directorates is available at http://www.afrl.af.mil

Taken as a whole, however, the AFRL technology effort related to fusion includes all the elements required: anthropomorphizing somewhat, effective eyes and hands connected with a brain. The sensing goal is development of a common operating picture robust with respect to sensor technologies, and the effecting goal is for speed and accuracy of threat response.

1.2 AFRL Partnering in Fusion Technologies

The AFRL also works closely with other military departments, with industry and other government agencies. The AFRL maintains a virtual distributed laboratory, of which the earlier mentioned fusion network is a part, to coordinate technology developments across the institutions involved.

The full range of fusion technologies is of interest to the Air Force, and the AFRL is working in a leadership role on many, if not most, of them. This role requires coordinating efforts of many research and development organizations. The science supported by AFOSR is conducted in many of these organizations and, when not, is connected tightly to them through the AFRL.

2 Fusion Science

The AFOSR supports research in areas related to fusion of information and data, including multi-spectral image sensing, fusion and processing for recognition and identification of targets, as well as integrated distributed

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2000**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**
4. TITLE AND SUBTITLE **AFOSR Research Programs in Image Fusion**		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Directorate of Chemistry and Life Sciences Air Force Office of Scientific Research Arlington, VA, U.S.A.**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release, distribution unlimited**		
13. SUPPLEMENTARY NOTES **The original document contains color images.**		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**UU**	**7**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

parameter control of the vehicles involved in these tasks. Main topics of research are considered in turn.

2.1 Sensors

The AFOSR supports research on sensing materials and devices for multi-spectral imaging. Some research supported in Biological programs takes inspiration from study of natural systems. The python, for example, can fuse the visible and infrared spectra to detect and capture its prey. Research supported in this program has recently determined [1] that the heat sensitive organ of the python may take advantage of specialized membrane structures that provide a degree of spectral filtering for underlying heat transduction mechanisms. The microstructure of the overlaid membrane, specifically, the spatial distribution of submicron pits within the membrane, is suspected to play a role in spectral filtering and is the object of current study. The overall goal of this research is to determine whether infrared or heat sensitive detectors might be operated at ambient temperatures with higher sensitivity and resolution than those available using current technologies.

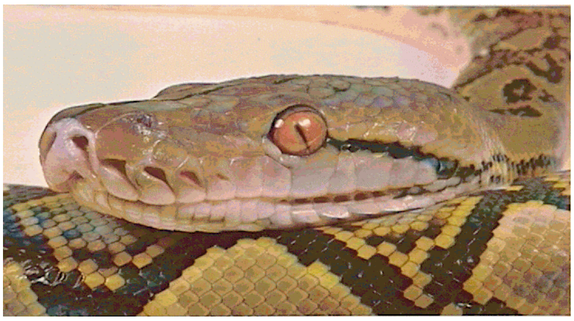


Figure 1 : Rattlers and Pythons Sense Visible and Infrared

In the optoelectronic materials program, AFOSR supports research on sensor materials for focal plane arrays and other devices, to cover the entire spectrum with fast, sensitive, high resolution images. Current approaches include quantum well infrared photodetection and quantum dot arrays. These approaches provide fast (picoseconds), sensitive (tens of milli-Kelvin), high density sensor arrays for a variety of applications.

The AFOSR optoelectronics materials program also supports research on integrated focal plan imaging of multiple spectral bands. The interspersed spectral images that result offer advantages in image registration and sensor fusion because images in multiple bands are obtained at the same time through the same optics.

One approach to integrated multi-spectral sensing involves construction of three by three pixel subarrays in which each of the nine sensing sub-pixels receives an image filtered into one of three infrared bands and one of three polarimetric orientations. Polarimetric images are of interest because man-made objects, with their planar surfaces, typically do not reflect light of all polarizations. Fused images can also be constructed to provide system operators and image analysts with new information that may be useful in separating man-made objects from natural backgrounds -- camouflage breaking.

In the approach described above, the infrared sensing material is obtained from novel 3-5 materials, spectral tuning is obtained using interference filters constructed of Germanium and Silicon Oxide, and polarimetric sensitivity is obtained using a standard grating technique.

AFOSR also supports research to combine multi-band optical and radar sensing elements into compact, low power, low weight modules. One current approach involves research at the fundamental device design level to develop common aperture devices for active and passive sensing of EO and RF. According to one notion for active modes, for example, LADAR illumination would be modulated at mm-wave frequencies so that return light might be detected simultaneously and demodulated with the radar returns for precise pixel registration of the two images.

It has been long known that interaction can occur between electromagnetic fields and various material excitations. Brillouin scattering results from the coupling of electromagnetic fields and acoustic waves in matter. For the first time, as far as we know, researchers working with the Air Force Office of Scientific Research are exploiting this electromagnetic-acoustic coupling to attempt to extend Air Force imaging capabilities.

In a real material medium such as foliage, wood, soil, concrete, or plastic, the material polarizability and material conductivity are dependent on the local pressure. Material polarizability refers to the degree to which fixed charge in the material can be distorted by an electric field. A measure of material polarizability is the dielectric constant. Material conductivity refers to the tendency of free charges within the material to move in the presence of an electric field. While polarizability and conductivity are functions of local pressure, these material properties also influence electromagnetic wave speed in the medium. Thus, there is a connection between pressure and the movement of electromagnetic energy, and, it is this interaction that is being exploited to enhance imaging.

Professor Thomas Banks [2] and colleagues at the Center for Scientific Computation at NC State University, under AFOSR sponsorship, have performed computational research that indicates that this electromagnetic-acoustic (pressure) interaction can be exploited to help identify materials. Banks and colleagues have worked at microwave frequencies and have shown that an acoustic wave front can act as a weakly reflective moving mirror within a medium such as soil. Using short microwave pulses and exploiting the vast difference between electromagnetic speeds in materials and acoustic speeds, acoustic wave fronts can be interrogated as they spread in a structure. Interrogating the acoustic or pressure fronts appears to be able to aid in the characterization of the material between the surface of the object and the “collision point” of the acoustic wave front and the microwave pulse.

This research is aiming at exciting military applications. Specifically, it is expected that underground bunkers will have air conditioning units or motorized airflow systems. These constitute a localized acoustic source that may be located using microwave scattering off of the outwardly moving acoustic waves. The research will also investigate whether vehicles with motors running have acoustic signatures that will permit identification in settings of high clutter. Finally, the earth has naturally occurring vibratory events. This research will ask whether scattering of these naturally occurring events can aid in the imaging of ground and sub-surface targets.

2.2 Mammalian Vision as Processing Model

The need for fast accurate scalable approaches to image fusion has partially motivated AFOSR investments in modeling of the human visual system and other mammalian systems of similar complexity. For example, These efforts are motivated by knowing that human image processing for recognition of objects in complex scenes is efficient, taking just a few hundred milliseconds in a few stages of neural processing. Processing, however, is characterized by complex local non-linear neural connections with plenty of feedback. Some of this complexity is evident in Figure 2, a drawing of mammalian retina provided to illustrate neural connections for initial multi-band registration of images, in three types of cone cell on the left, and the following adaptive contrast enhancement and encoding into separate chromatic image streams.

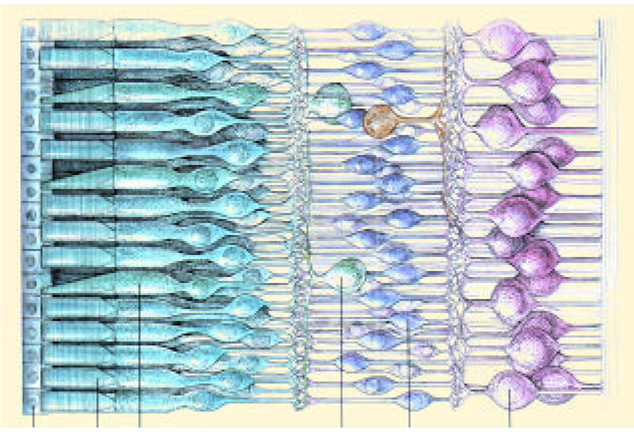


Figure 2: Retina provides multi-band encoding for fusion

processing

AFOSR focuses on discovering algorithms based on models of these and later stages and their algorithmic support for human and computational processing of complex scenes. Models are expressed formally and developed into complex neural network architectures with important features for image processing. Such encoding and processing appears very efficient, as described for the natural system, and is robust with respect to desired task performance. For example, the retinal encoding represented in Figure 2 supports a variety of human visual tasks: motion processing for navigation and computation of depth maps; stereo processing for position and depth maps in support of reaching; texture processing for material characterization; contour detection and completion for edge typing and surface identification; and, of course, the segmentation of objects from their backgrounds and their rapid recognition and identification.

Retinal processing proceeds at multiple spatial scales and temporal resolutions through organized sets of spatio-temporal and chromatic filters defined by their so-called weighting functions. In general, these image weighting functions and their interactions are defined locally and, as a result, bear some similarity to current wavelet based approaches. (According to reports, the first patent on wavelet-like self-similar basis sets for image processing was awarded almost twenty years ago to a researcher in human vision). Image fusion techniques based on discoveries in retinal and cortical models of vision tend to proceed from coarse to fine spatial scales. Additional models based on cortical processing add many important features to the retinal models, including algorithms for precise registration of contours that, depending on the spectral band of an image, may be offset or missing.

AFOSR supported models of mammalian visual processing have proven useful in the contexts described above. Algorithms for stereo vision have been employed to create depth maps used to guide reaching and grasping in robotics applications. Algorithms that process image sequences have proven useful for collision avoidance in autonomous navigation. Algorithms for texture detection and discrimination have proven useful in contexts of material classification and, with continued work, may prove useful in terrain characterization. Algorithms for contour detection and completion are beginning to merge with algorithms for shape encoding for identification. Algorithms for learning and classification of image and other data have proven useful in a variety of contexts as will be described later. Lastly, models of image encoding have inspired novel techniques for false color display of multi-spectral images. Approaches to these techniques of image display are outlined next.

2.3 False Color Display of Fused Imagery

Data representations for fused images are important to the Air Force in a number of applications. Those for automatic recognition are discussed in later sections. Here, displays for human operators are emphasized. The human operator, whether on-line wearing a head-mounted display device or off-line performing tasks of image analysis, represents a large and growing consumer of fused imagery. For example, the U.S. Congress has called the need for additional scheduled launches of reconnaissance satellites into question because the number of image analysts available seems insufficient to process the increased volume of image data. The AFOSR program in Human Performance is considering ways to address the need for increased capacity in image analysis. The approach under discussion would supply the analyst with a more refined image stream, one preprocessed according to rules discovered by study of the experts involved.

The most straightforward approach to false color display of multi-spectral imagery involves, roughly speaking, driving each of the three phosphors in a color display device with an image stream obtained in a different spectral band. An approach similar to this is taken in an AFOSR-supported effort to assess ways that operators benefit from novel head-mounted devices that display polarimetric images superimposed on monochromatic images of the same scene. As described above, such fused displays may be useful in breaking camouflage of manufactured items such as tanks or other ground vehicles.

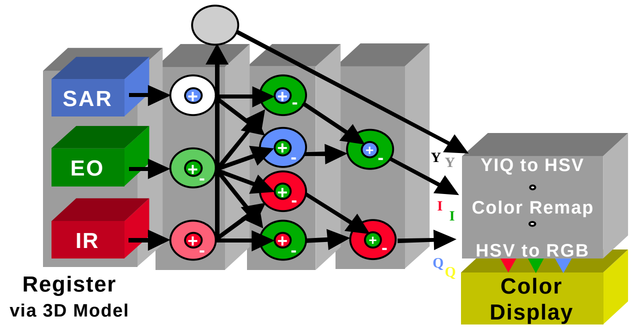


Figure 3: Image fusion architecture based on neural models of human vision

Models of mammalian visual processing have been adapted for contrast-enhanced display of multi-band image streams derived from visible, infrared, radar and other image types, such as polarimetric. Alan Waxman, for example, has derived a number of architectures for multi-band image processing and display. Typically, each includes three stages of post-processing as illustrated in Figure 3. The first stage involves normalization and contrast enhancement within a band, processes similar to those of the retina. The second stage, which can be hierarchical as shown, involves processing between bands, in a fashion similar to that of "double opponent" processing in human color vision. This second stage helps to locally de-correlate the image streams and can be used to create new streams from weighted versions of multiple input streams. Lastly, the resulting images are mapped to drive intensities in a color display.

The architecture shown in Figure 3 is one example of several developed by Alan Waxman, the results of which will be demonstrated in a later paper [3]. Architectures have been developed for more than three input streams, and some have been implemented in hardware for feed-forward processing at speeds exceeding the frame interval. In summary, such techniques offer a fast scalable approach to image fusion

No standard multi-band processing or display color-mapping scheme is yet available. The human factors of such displays are just beginning to receive attention. Converging on a set of standards for image fusion and display may benefit the Air Force through savings in bandwidth and speed of processing. For example, the fused products of multi-band images might be transmitted from sensor platforms instead of the raw image streams. For example, lossy compression schemes might be developed based on the needs of human viewers reflected in the models of human visual processing. An extreme example of such compression, also studied under AFOSR support, involves trading field of view for spatial resolution in displays with pixel resolution that declines from the image center to match the decline in spatial resolution of the human retina. Such displays may have use for human in the loop applications where size and weight of processing and display hardware is at a premium.

2.4 Category Recognition and Learning

AFOSR has supported theory and modeling of human pattern recognition and decision making, informed by human and animal experiments and descriptions of information processing in cortex and other brain regions. For example, a family of neural network models of category learning and recognition developed by Gail Carpenter at Boston University has proven useful in a variety of applied contexts, including pattern recognition in multi-spectral fused imagery. One example [4] from the family of architectures based on Adaptive Resonance Theory is illustrated below.

The pattern recognition, feed-forward, aspect of the neural architecture illustrated in Figure 4 can be essentially described as a pattern classifier, to define clusters in the space of input features, topped off by a system for mapping these recognized patterns to equivalence classes under the application of interest. During feedback learning, the weighted inputs to definitional nodes for patterns and for classes are adjusted according to rules derived from theories of cognition and learning. Learning at the pattern recognition level can proceed automatically, under management of a parameter that determines precision of match in the feature space. Learning in the classifier proceeds under supervision, say, of a human expert in the application domain.

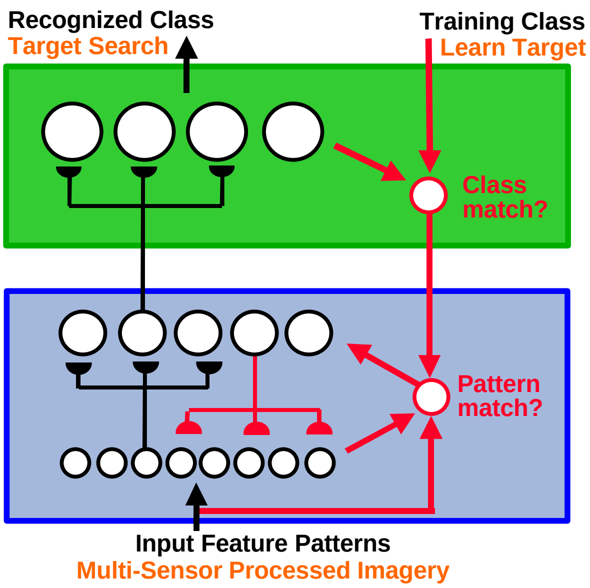


Figure 4: ARTMAP architecture for recognition learning

Neural architectures, such as ARTMAP, based on theories of Stephen Grossberg [5], have proven capable of fast stable learning from large noisy data sets where the classes of interest are arbitrarily defined. Application domains include engineering design reuse, 3D object recognition, sensory motor control and navigation, and others, including satellite remote sensing. For example, a current project on satellite remote sensing, not supported by AFOSR, involves use of Landsat data and terrain data to identify classes of vegetation, their mixtures and their changes over time. ARTMAP performance in this domain exceeds the speed of human experts and appears to match them in performance.

Alan Waxman and colleagues have begun to use the ARTMAP architecture to learn and subsequently recognize classes of objects defined in the feature space of multi-spectral images. For example, the fused images generated according to processes described in the previous section are supplied to analysts who identify image regions containing examples (and counterexamples) of objects of interest. Subsequent to learning, ARTMAP processing of new images can be used to highlight image regions with similar features. The use of ARTMAP as an aid to image analysis will be illustrated in the later talk of Dr. Waxman [6].

2.5 Shape Coding and Matching

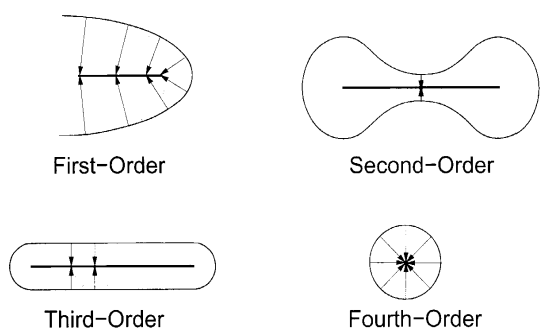
AFOSR also invests in the study of ways that humans learn and recognize image shapes. The goal of this research is to provide image-processing systems with the accuracy and the flexibility of human observers while greatly increasing the speed of processing compared to the human benchmark. The topic of shape coding is germane to this meeting because desired object coding schemes must be robust with respect to multi-spectral data in which the generation of shadows, occlusions, and missing contours may follow different physical laws. Of equal importance is the potential benefit of using information, such as contour information, from one band to constrain computations on images from another band.

AFOSR does also invest in research topics that may precede human image coding and support it. These topics are omitted from discussion in the interest of brevity. Such topics include contour identification and completion, surface characterization and completion, shape or shape parts from structure or motion or texture or parallax or shading etc., and depth from stereo. These topics are important, and may need to be resolved in the context of multi-spectral imaging, but are more central to discussion at meetings more directly concerned with automatic target detection and recognition.

The demonstrations of Dr. Waxman, however, point the way to object detection and recognition in fusion contexts. In those demonstrations, image regions containing multi-spectral features associated with targets can be identified and associated with target classes of interest. This approach, then, may provide effective cueing for shape recognition algorithms that can operate on the fused image data.

AFOSR supports research on shape recognition and shape matching. One example is provided in the work of Steven Zucker at Yale University. This approach uses bounded image contour regions as input, and initiates a diffusion process that produces shocks along curves (Blum's medial axis) interior to contour-defined regions. The shocks are classified into four types determined by the shape of surrounding contours, as shown in Figure 5. The shock-defined curves of an object connect, and the pattern of connections can be expressed as a graph to provide a complete skeletal description of the object. Experiments of Zucker and colleagues [7] have demonstrated that the skeletal graphs provide a fast and effective means of generating shape descriptions from images and comparing them to stored descriptions for recognition. These experiments also demonstrate that the shape comparisons based on skeleton graphs appear robust with respect to scaling, rotation, deformation (e.g. perspective), and occlusion.

This approach may lead to image processing technologies of interest to the Air Force in applications where fast and accurate identification of objects is a premium. For example, in surveillance or targeting of large numbers of ground objects – which may be similar (but differ in value, e.g. tanks/trucks, friend/foe), or articulated (e.g. having slewable or extendable parts), or partially occluded or camouflaged – both image analysts



and missile seekers may benefit from object-based templates few in number that support a similarity metric.

Figure 5: Four shock types, primitives for skeletal object descriptions

The approach to object template matching described above is based on object 2D outlines or, equivalently, object silhouettes. Interestingly, 2D silhouettes may partially account for object recognition in human observers. Recent work of Patrick Cavanaugh and colleagues at Harvard University has demonstrated that object templates based on silhouettes (more precisely, 2-tone images that may contain object information in light or dark regions) may be sufficient to account for human recognition of familiar objects. In a series of experiments [8], this group demonstrated that recovery of object parts from image data is not required for object recognition in 2-tone images. Recognition of familiar object is fast and veridical. An example is provided in Figure 6.

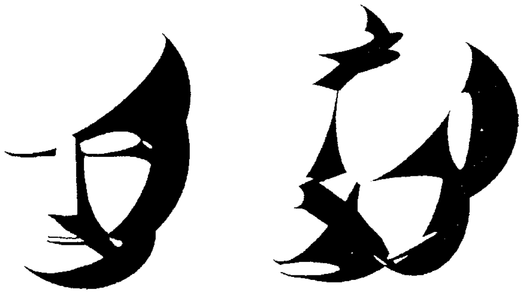


Figure 6: Familiar and unfamiliar arrangements of same volumetric parts

Additional AFOSR-supported research is underway to determine how an object's 2D contours might be reliably acquired from noisy image data with occlusions and shadows that may interfere with algorithmic attempts to produce object outlines. Fused sensor imagery may ease this task. In combination, however, the work described above provides some optimism that 2D templates, relatively few in number, may provide a robust method for fast and accurate identification and graded discrimination of highly similar objects.

2.6 Adaptive Control

The AFOSR supports research on dynamical control of distributed parameter structural systems for space and flight control systems for air vehicles. Among other approaches, these programs seek understanding of processing, computation, and control found in biological systems simple enough to enable system-level descriptions of them, yet complex enough to display performance characteristics not fully understood.

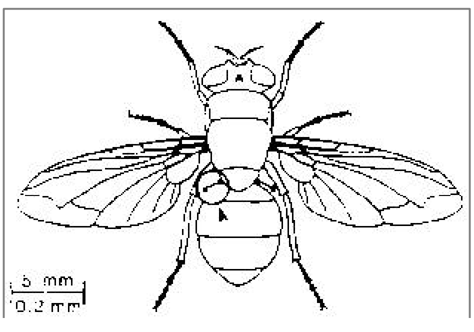


Figure 7: Sensory-motor fusion for adaptive control

Such research is expected to contribute to development of new technologies for autonomous operation of uninhabited air vehicles, munitions, and satellites, working a variety of missions perhaps in cooperating swarms.

Past AFOSR supported work has led to demonstration of neural architectures that merge sensory maps of the environment with motor maps of the local space to generate essentially a look-up table for motor commands to execute movement to a desired location from any starting position. Further, the resulting sensory motor maps support a degree of adaptation to changing physical plant due to loss of calibration, damage, changes in mass, or other perturbations.

3 Summary

The AFOSR supports basic research supporting all aspects of an idealized closed-loop system capable of searching complex environments for objects of interest, deciding appropriate actions, and taking effective actions to alter the environmental landscape. Each of these idealized capabilities relies heavily on fusion of information and data. In sensor programs, AFOSR attempts to discover new ways to acquire multi-band images in a single device. In signal processing and cognitive programs, AFOSR attempts to discover new algorithms for processing multi-sensor data in support of decisions on target identification. Lastly, in guidance and control programs, AFOSR attempts to discover novel approaches for autonomous control of air and space platforms.

These basic science programs, of course, support a number of approaches but in each is found some study of biological systems. Biological systems are efficient, so their study can provide very good information about *what* to compute. *How* to compute can take full advantage of modern technologies, so the speed and flexibility of biological systems might be greatly exceeded in implementation.

The scientific programs of AFOSR support research in both foreign and domestic institutions. A description of AFOSR programs, and links to Internet sites of the foreign liaison offices can be found at http://www.afosr.af.mil.

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