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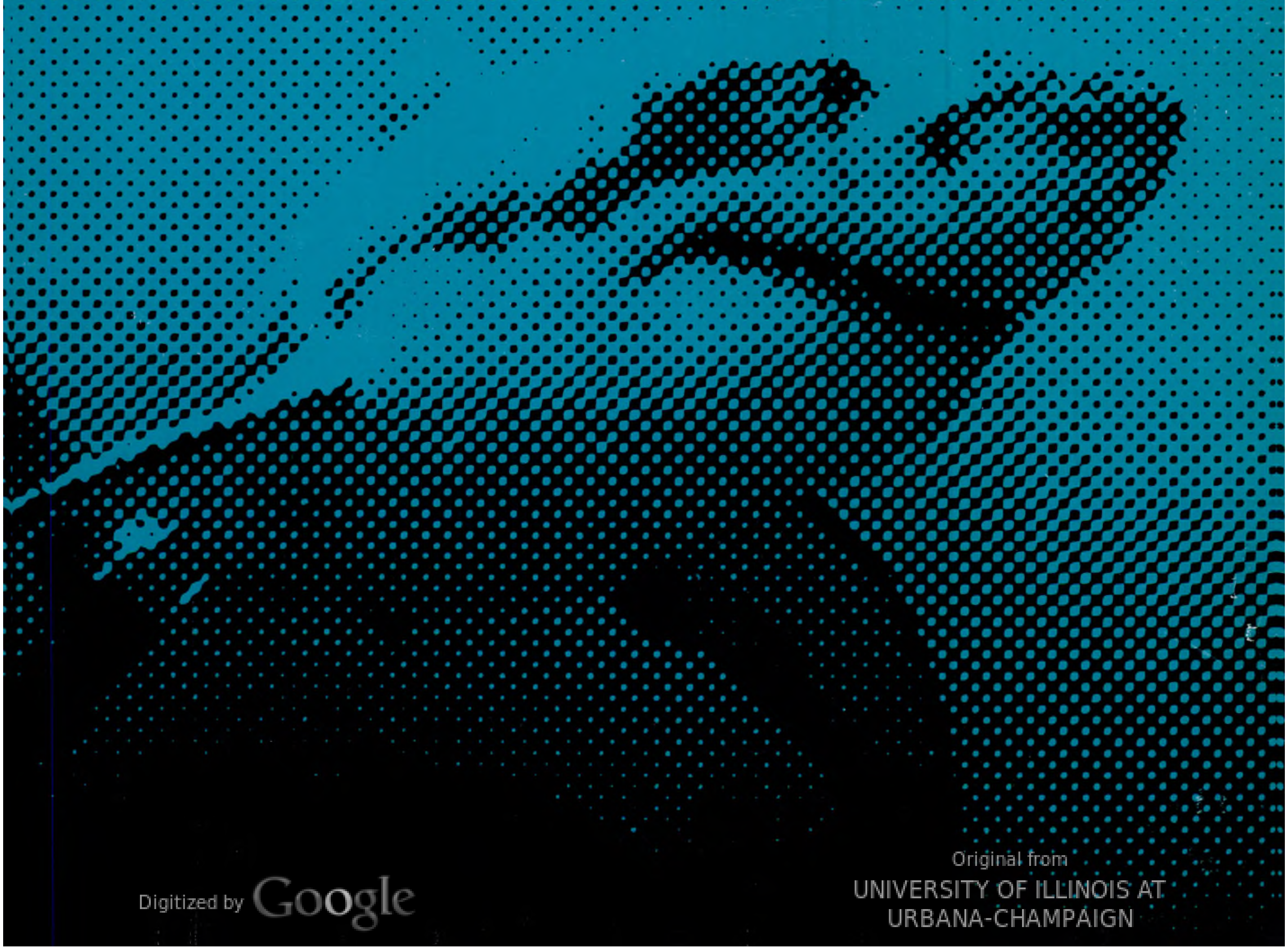
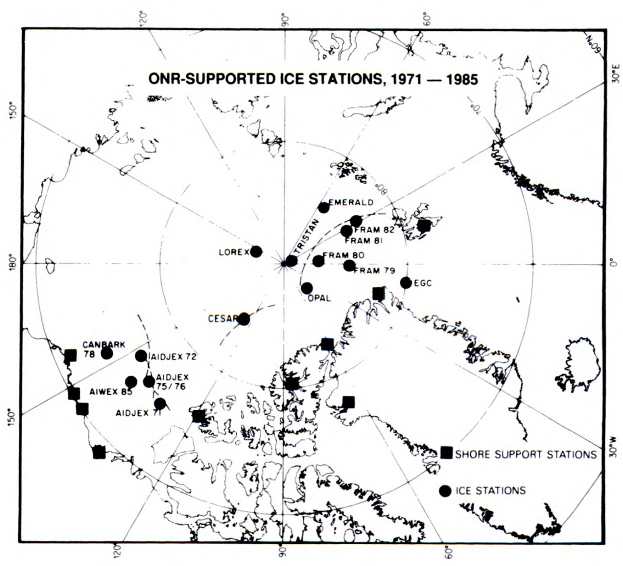


Office of Naval Research's Ice Stations

An AIDJEX ice station in 1975

Acoustics station on T-3 in 1969



An ONR sponsored program of manned ice camps where scientists can work and live for long periods of time started in the late 1940's. Initially the camps were situated on thick pieces of glacial ice (100 or more feet thick) which are stable and last for decades, such as the ice island known as T-3 or Flecther's Ice Island. Ice islands of this type are rare as very few glaciers drift into the Arctic Ocean. Since 1948, T-3 was used as a research station by various groups. From 1961 to 1974, ONR maintained the station for its Arctic research programs.

Starting in the 1970's ONR shifted to manned camps on thinner mobile sea ice. Logistic and support techniques have been perfected to the point that such camps are now routine for Arctic research and are used to support under-ice naval operations. Ice stations were the research and equipment platforms for the Arctic Ice Dynamics Joint Program (AIDJEX), a large scale study of sea ice in its environment, which was funded by ONR from 1972 to 1976. Since then there have been a series of sea-ice operations under ONR sponsorship.

Up-to-date information on the extent, position, thickness, and break-up characteristics of sea ice are vital for Arctic naval missions. Under-ice navigation depends on better knowledge of under-ice contours, under-ice sonar propagation, through and under-ice communications as well as basic oceanographic and ocean physical measurements. An understanding of the large scale response of sea ice to its environment is needed for solving many important practical and theoretical problems ranging from the interaction between the ice cover and global circulation to navigation on and under the Ice-covered sea.

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Representation of a great white shark from a photograph taken off the southern coast of Austrailia. See article on page 2.

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WHY DO SHARKS ATTACK HUMANS?

by Samuel H. Gruber
University of Miami

The primary interest of the U.S. Navy in shark research is to develop means of coping with the shark hazard to men and equipment in the sea, particularly for naval personnel under survival conditions or during swimmer/diver operations. During World War II when service men were victims of air and sea disasters and met sharks in their own environment, often with tragic consequences, the U.S. Navy gathered a team of experts to produce a solution. This was the beginning of major shark research efforts which were expanded and highlighted by the creation of the Office of Naval Research sponsored AIBS Shark Research Panel in 1958. The panel coordinated more than 100 studies of the biology and behavior of sharks in many parts of the world; and several panel members tested more than 200 chemical compounds, biological products, and physical devices for their deterrent effects on sharks while fulfilling their practical objectives. These tests, as well as the basic research studies, disclosed new facts about the biology and patterns of behavior of many species of sharks.

H. David Baldridge and C. Scott Johnson in their article "Antishark Measures" (Naval Research Reviews, 23(3), 15-22, 1969) reviewed the various antishark devices and procedures then available. They emphasized the importance of "good shark sense" and that the knowledge about these animals is "without a doubt our most valuable weapon against shark attack." With this rationale, the Office of Naval Research has been supporting basic research on the biology and behavior of sharks in the wild and laboratory. Information obtained was used not only to develop more effective antishark measures, but to provide better advice to personnel on how to avoid or minimize the risk from encounters with dangerous sharks.

During the last 20 years, ONR supported scientists have learned much about the shark's sensory capabilities (visual, acoustic, chemical, and electrical), and this information has greatly furthered our understanding of shark attacks. Recently through telemetry devices, ONR scientists have found out about the daily behavioral routines of active sharks in the wild. The findings of these ONR funded research programs are discussed in this article, and it is noteworthy that many of these findings have contributed to our basic understanding of shark bite problems of importance to both industry and the Navy.

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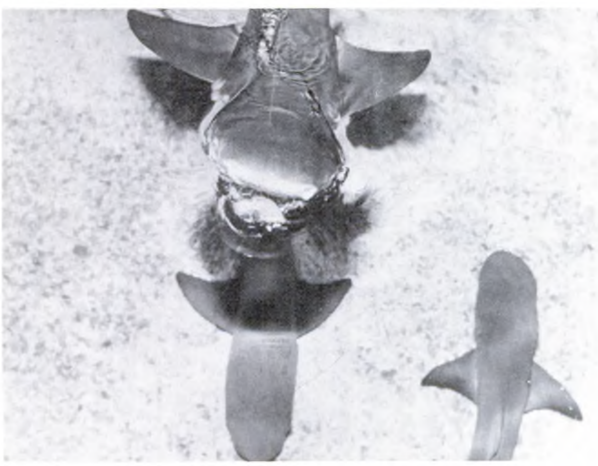
Introduction

To begin to understand the problem of behavioral causation, one must first appreciate that the activities of higher animals such as vertebrates are driven by external stimuli as well as internal states. In other words, sharks are not simply automatons strictly controlled by environmental cues impinging on their sophisticated sense organs. Rather, their behavior results from a mix of external and internal stimuli (Figure 1). That this is true can be shown by our feeding studies on captive sharks.[1] Even a highly active predator such as the lemon shark will completely ignore food when sated after a meal. Why? Because an internal state we call, for lack for a better term, "its feeding drive" has been lowered; and we say that its "feeding motivation" is below the threshold for appetitive feeding behavior.

Figure 1

Captive young lemon shark being fed a measured amount of food in a feeding experiment.



One of the most graphic if not terrifying descriptions of how a shark might "decide," based on external cues alone, to attack its victim comes from Peter Benchly's smash hit novel *Jaws*. With the author's permission, I abstract some of his writing here (Figure 2):

Figure 2

The great white shark: super predator (courtesy of J. Stafford-Deitsch)

"The great fish moved silently through the night water propelled by short sweeps of its crescent tail . . . . The eyes were sightless in the black and the other senses transmitted nothing extraordinary to the small primitive brain . . . . A hundred yards offshore the fish sensed a change in the sea's rhythms. It did not see the woman nor yet did it smell her. Running within the length of its body were a series of canals, filled with mucus and dotted with nerve endings and these nerves detected vibrations and signaled the brain. The fish turned toward shore . . . . The vibrations were stronger now and the fish recognized prey. The sweeps of its tail quickened . . . . The fish smelled her now and the vibrations—erratic and sharp—signaled distress. The fish was about forty feet from the woman, off to the side, when it turned suddenly to the left, dropped entirely below the surface and with two quick thrusts of its tail, was upon her."

Benchly then describes, in some detail, the fatal attack by a white shark on a young woman. The description is mostly from the point-of-view of the predator. Clearly, Benchly did his homework. He combined information about shark senses with a vivid imagination and a gift for writing to hold the reader in absolute suspense.

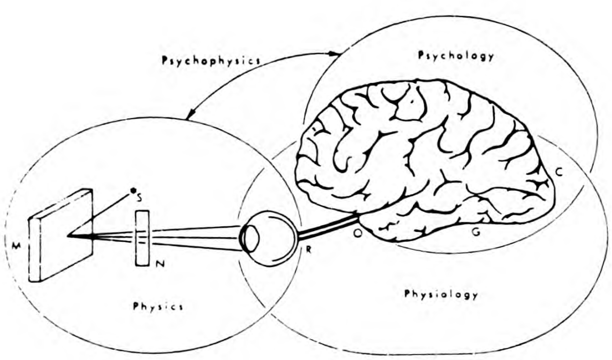
However, Peter Benchly's description points up two nearly insurmountable problems with trying to predict the behavior of sharks (and for that matter most other higher animals). First, nothing is mentioned about the internal or drive state of the shark. Indeed sharks are often called eating machines, but as I mentioned above[1] this is simply not true. The fact is that, while the sense organs even of large sharks are readily amenable to investigation, psychologists and ethologists (biologists that study animal behavior) cannot specify the physiological substrate of a particular drive. How then can we predict with any sort of validity the drive-state of something as wild and immune from investigation as an attacking white shark (Figure 3)?

The second problem is insurmountable: Benchly's description notwithstanding, we simply cannot know what is in the mind of an animal. It is easy to forget that an animal's sense organ communicates with its brain. So, if we find, for example, that an animal has an excellent eye, we must recall that it is always the brain which determines what becomes of visual information collected by that eye. And to understand how an animal's brain interprets the vast array of sensory data streaming in from the external world requires experimental techniques that are not applicable to large, wild animals like the white shark.

Such an introduction suggests pessimism about *answering* the question "why sharks attack humans." However, it is possible to speculate on the motivating factors underlying shark attack. But first, some discussion of what is meant by motivation and drive-states seems appropriate.

Figure 3

The three domains of color vision. The physical stimulus (S) consists of reflected quanta from matter (M) which pass through a transmitting substance (N) and into the eye, where they are absorbed in the photoreceptors. The physical stimulus is transformed in the retina (R) to a physiological stimulus, which is transmitted to the brain via the optic nerve (O), where it is further processed physiologically at the geniculate nucleus (G) and the straite cortex (C). The locale where physiology grades into awareness (i.e., phychology stimulus) is not precisely known. However, as shown, psychophysics is the systematic attempt to relate the physical stimulus to perception, with the goal of understanding underlying functional mechanisms. (Sheppard 1968. Reproduced with the permission of the author and publisher.)



Motivation

There are two broad disciplines which deal with the behavior of intact animals, ethology and psychology. The aims and goals of these two important academic sciences are somewhat different (see reference 2) and as expected, their views of motivation are also different.

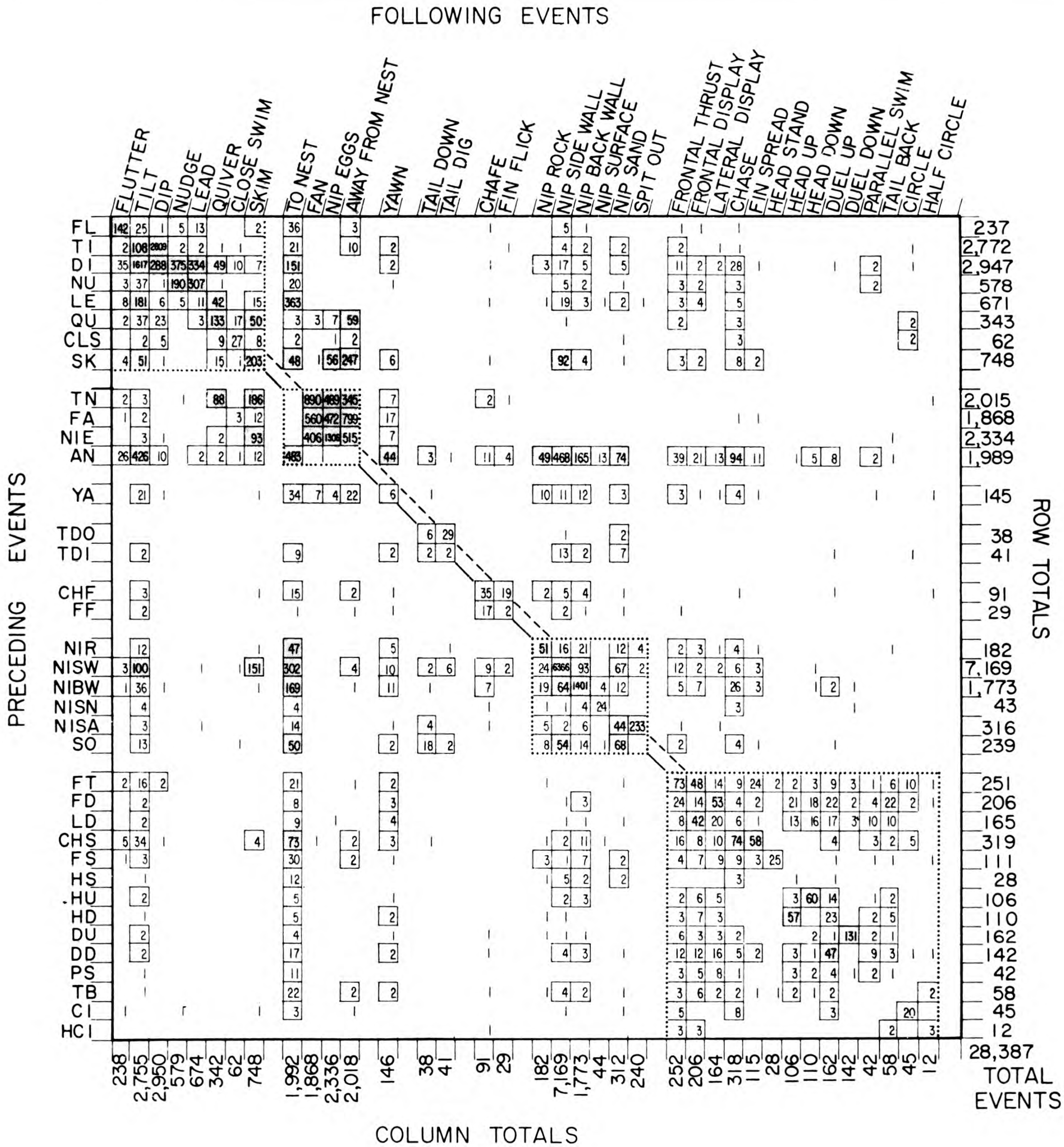
The word "motivation" is derived from the noun "motive" which literally means "causing to move." One definition of motivation in lay terms is an emotion, desire or physiological need, acting as an incitement to action. From this rather simple definition spring volumes of difficult and other contradictory behavioral theory. The study of motivation has been called a quagmire[3] and indeed after 50 pages of detailed explanation Bartoshuk[4] was forced to conclude that there is no general solution to the problem of how behavior is influenced by motivation. Nevertheless, both ethology and psychology have tackled this very thorny issue.

From the ethological viewpoint, motivation and drive are basically short- and long-term versions of the same phenomena: the ability of animals to switch their behavior priorities. Motivation may be considered as a recurring "hunger" which must be satisfied,[3] and as mentioned, elaborate theories have been proposed to explain what a drive is and how motivation works. None of these theories has been entirely successful. (Figure 4).

The ethological approach to the study of motivation is appropriately called "motivational analysis." This extremely difficult and time-consuming procedure involves continuous long-term observation during which the sequence of several previously known behavior patterns is recorded and correlations between these patterns are computed until the observer is able to derive a model expressing the relationships among these patterns of behavior.[5] The point is that motivational analysis is a very difficult procedure and it is unlikely that any dangerous shark will be so analyzed in our lifetime. Thus, to fully answer the question of "why sharks attack humans" we must understand both the external stimuli directing the shark – and this may be possible and also the internal drive-states – and this is presently impossible.

Figure 4

Sequential contiguity table showing data on 40 different behaviors of a small fish. Such complex analyses are required to understand animal motivation. (Courtesy of the author and Dr. A. A. Myrberg, Jr.)



The framework of experimental psychology can be used to investigate motivation and drive in sharks. Indeed, I have done several studies of learning and behavior of sharks under ONR support (see reference 2) in which motivation played an important role. For example, if one wished to shape a behavior such as a visual discrimination using food as a reward, the shark must first be willing (i.e. motivated) to feed before training proceeds. In such a situation, the shark's motivation is controlled by withholding food until the hunger drive increases. Analysis of such "deprivation experiments" is basic to the (psychological) study of motivation. However, the experimental analysis of behavior at the choice point of a discrimination maze is a far cry from understanding why a shark chooses this victim over that at any particular time. It must be concluded that shark attack in the usual sense of the word is not presently subject to experimental analysis (who would volunteer to be the guinea pig?). Therefore, any theory about motivation or drive-level in the context of shark attack cannot be subjected to hypothesis testing and so it would be impossible to choose rigorously among alternative hypothesis as to the cause of one or another attack.

Still, as mentioned earlier, we need not be entirely pessimistic about understanding the motivation behind shark attacks. While hard data will not be available, we can speculate and, in effect, make some well-educated guesses about why sharks attack men and less frequently women.

Figure 5

Slash wound on the leg of a diver inflicted by the upper teeth of a blue shark. (Courtesy of R. Taylor)

Types of Motivation

When considering shark attack, we are definitely *not* confronted with an infinite array of motivational variables. Although shark behavior may be considered poorly understood, what we do know suggests that sharks behave in a way compatible with the rest of the aquatic vertebrates. Thus it is reasonable to assume that a shark's drives are not that of an alien creature but rather fall into the same basic categories as their fish-like relatives, the teleosts (and for that matter, the other vertebrates including man). These categories have been called the big four: feeding, fear, sex and aggression[6] (Figure 5).

In the context of a shark attack, here defined as a relatively forceful physical contact by a shark—a bite, slash or hit—directed at a victim or his gear[7] it is certainly possible to speculate on the motivating factors leading to such a shark-human interaction. And these probably reduce to just two: motivations during *predator-antipredator* behavior and those of *social* behavior. There is a third category which I call, for lack of a better term, "reflexive biting or attack." Here, the shark may be compelled to bite just as our knee jerks when the patellar reflex is activated by a blow to the patellar ligament. At the moment of the bite, no motivation is involved. Kalmijn[8] demonstrated that sharks detect and orient to minute electrical fields emanating from their prey. He also showed that sharks will attack a battery-driven electrical source mimicking the natural (fish-driven) field. Kalmijn[8] believes that when confronted by such an appropriate electrical stimulus, a shark is forced to bite irrespective of any prevailing drive-state. Similarly, forced movements form the basis of electrical fishing in which fish are compelled to swim to an electrode producing an intense electrical field. The motivation of the fish has little to do with its movements. However, it is unlikely, except under very specific and unusual circumstances, that a "reflective attack" on humans might occur. On the other hand, due to stray but appropriate galvanic fields, attacks on boats, oceanographic gear and other metallic objects might well have a strong component of the "reflexive bite" (Figure 6).

Figure 6

Great white shark biting a metallic boat. Stray galuanic fields from the hull may have evoked a "reflexive bite." (Courtesy of R. Fox)

We now turn our attention to predator-antipredator and social motivating factors for it is these that surely account for the majority of shark attacks. At the onset, it should be made clear that there is not a single dangerous shark, but rather a diversity of sharks. About 50 species have been implicated in shark attacks[9] and these range in size from less than 2m (a 35 cm lemon shark chased down and bit the foot of a colleague in about six inches of water – D. Nelson, personal communication) to over 6m in the case of the white shark. The feeding habits of these 50 species vary from generalized feeders like the tiger shark to rather specialized feeders such as the blacktip reef shark (Figure 7). There are those that feed on large prey such as other sharks and marine mammals and those that are strictly fish or invertebrate eaters. So the motivations for an attack depend not only on the behavioral situation (i.e. the external stimuli) but the type of shark as well (Figure 8).

Figure 7

The tiger shark. (Courtesy of Doug Perrine)

Figure 8

Jaws and teeth of a great white shark in action. (Courtesy of J. Stafford-Deitsch)

Since the majority of attacks involve jaws and teeth, we can profitably ask: Under what conditions do sharks bite?

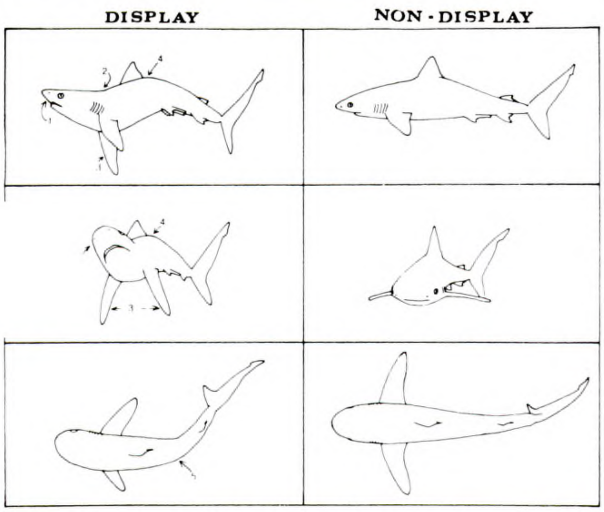
Predation: Sharks, like many other acquatic predators capture prey with their teeth and jaws (Figure 9). The teeth catch and hold the prey and in some cases have other functions such as cutting, gouging or crushing.[10] But in many species, the mouth cavity can be activated like a suction pump. Thus prey can be sucked in and swallowed whole. Even the largest, most dangerous sharks have this capacity.[11] The point is that the primary motivating factor for the coordinated use of jaws, teeth and mouth in nearly all sharks is *prey capture*. However, they do use their teeth in other situations (Figure 10).

Figure 9

Great white shark prior to biting. (Courtesy of J. Stafford-Deitsch)

Figure 10

Comparison of non-display and display postures in the gray reef shark. Arrows denote: 1) lifting the snout, 2) bend between chondrocranium and spinal column caused by lifting of the snout, 3) pectoral fin depression, 4) arching of the back and 5) lateral bending of the body,



Antipredator-defensive: When threatened, some shark species such as the grey reef shark are known to perform postures which Nelson and his students have called agonistic displays.[12] Agonistic displays are signals which communicate both fear and aggression and indicate an animal's willingness to fight. One example is the snarling of a dog.

Using a one-man wet submersible, Nelson et al.[13] demonstrated that when grey reef sharks are chased into the reef with their escape-route partially blocked an agonistic display consisting of exaggerated, sinuous swimming is released. As the chase continues, the display becomes more intense until a point is reached where the shark launches an all-out attack on the submersible (Figure 11). This is an example of the use of jaws and teeth in a non-feeding context. Surely the shark didn't want to eat the sub (although I can't prove it), for the "agonistic" attack consists of a high speed bite after which the shark rapidly departs. Nelson[13] believes that this particular type of attack represents an antipredator strategy in which the gray reef shark attempts to discourage a pursuing predator.

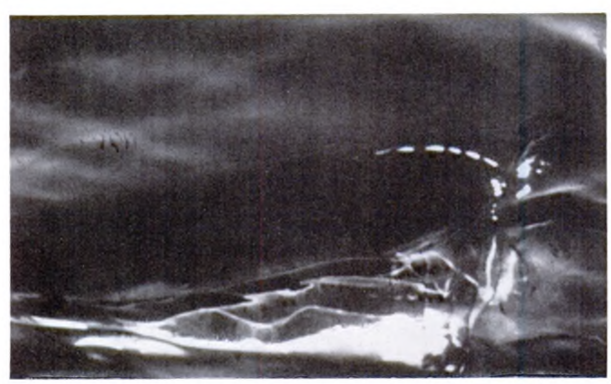
Figure 11

Gray reef shark attacks submersible after being chased into the reef-face. (Courtesy of A. Giddings)

Social factors: Another possible interpretation of Nelson's observation is that the grey reef shark is trying to protect its resources by evicting an encroaching shark or other large predator from its home range (Figure 12). Similarly, McCosker (personal communication) reported that a white shark attacked and badly wounded a small conspecific in the presence of bait and chum. In this case, the smaller shark was not eaten and the bite appeared to be a slash rather than a true bite. McCosker believed that the larger shark was trying to exclude the smaller one from the feeding situation.

Figure 12

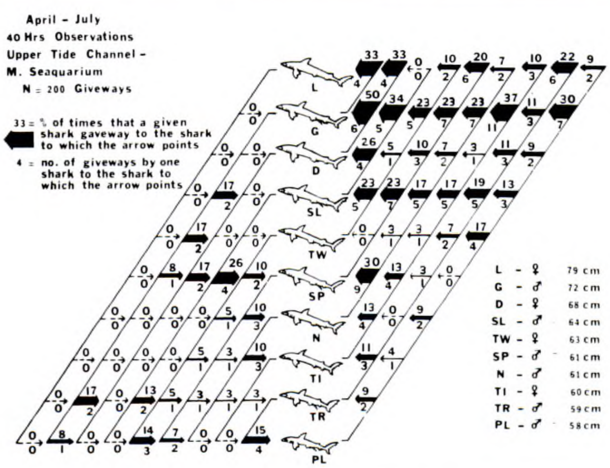
Laceration on the head of a young white shark inflicted by a larger conspecific shark of the same species. (Courtesy of J. McCosker)



Aggression: Curiously, those sharks whose behavior has been studied in detail do not seem to be very aggressive toward conspecifics (Figure 13). For example in our ONR supported bonnethead shark study,[14] we found little competition for food among the 15 members of our study colony. In fact, we never observed fighting (with jaws and teeth) under any circumstance during the six-month study. Yet the colony was socially organized into a size dominance hierarchy with the largest females at the top. Apparently the bonnetheads were able to organize themselves without fighting (Figures 14 and 15).

Figure 13

The social organization (based on Give-ways) shown by a study colony of bonnetheads during a four month period (April-July). Individuals had resided together for two months prior to the initiation of data collecting. (see reference 14)



We commonly think of animal fights in the context of territoriality. But again, I am not aware of any evidence showing that sharks will hold or defend a specific geographic site. While several species are strongly site-attached, in each case they tolerate conspecific intruders very well. The nurse shark, for example, can be found resting in caves with dozens of others stacked up like cordwood. Similarly, several individuals of the reef whitetip shark will remain in the same cave during daylight hours and return the next day after foraging at night.[15]

The point is that many shark species do not display intraspecific aggression, and at least the more social species tolerate one another reasonably well. The extreme danger presented by their teeth and jaws may require sharks to show restraint – in an evolutionary sense – to their conspecifics.

Figure 14

The nurse shark. (Courtesy of Doug Perrine)

Figure 15

The reef whitetip shark. (Courtesy of J. Stafford-Deitsch)

Sex: There is one context in which jaw and teeth are used to an extent only exceeded by predation (Figure 16). During courtship, the males of many types of dangerous sharks repeatedly bite the females on the back and flanks as a prelude to copulation. This use of teeth is such a non-feeding, social context produces so-called mating scars frequently found on mature, female sharks. Interestingly, very similar "mating" scars and wounds have occasionally been found on males. Were these simply spurious courtship activities or did males actually fight over access to a female?

Figure 16

Fresh mating scars on the flank of a lemon shark. (Courtesy of R. Jureit)

Analyzing Shark Attacks

From the foregoing, it is clear that sharks use their teeth and jaws, not only for predation, but for self protection, resource protection and in other social situations. Thus it seems that hunger motivates sharks to bite, but fear, aggression (rarely?) and sex are also motivating factors for the use of teeth and jaws.

By looking at the conditions of shark attack, the species involved and the outcome of the attack on the victim, it is possible to make an educated guess as to the motivation behind the attack. As late as 1878, the famous British ichthyologist, Day, wrote that sharks were motivated by factors such as affection, grief and disgrace. More recently, shark experts such as Victor Coppleson[16] and David Davies[17] believed that feeding motivation was behind most if not all attacks. Coppleson advanced a theory that attacks were essentially non-existent in waters cooler than about 20°C because sharks cease to feed below that temperature. Davies confirmed Coppleson observations for attacks in S. Africa but pointed out that, although rare, attacks did occur below 20°C.

It was David Baldridge who first suggested that Coppleson had misinterpreted the data. In a landmark paper and in his subsequent book, Baldridge[18, 19] noted that many attacks occurred below 20°C especially in cooler waters where white sharks swim. However, his most important points were that: 1) cold water inhibits recreational swimming so that the greatest bathing population (and thus number of potential victims) are found in waters above 20°C; and 2) from an analysis of wounds on bathers, he concluded that other motivating factors besides feeding must be operating. His overall conclusion was that the only significant factors with regard to the probability of being attacked were the number of potential victims and the number of potentially dangerous sharks occupying the same waters at the same time. In other words, exposure appeared to be the critical factor in shark attack rather than factors such as temperature, depth or time of day. There were, of course, special cases such as air/sea disasters and "feeding frenzies" where a very different set of factors operate.

Baldridge[19] pointed out one other important fact about the analysis of shark attacks. To reveal the true cause of an attack or to assess the actual danger to any particular bather, data on environmental factors as well as the number of bathers on days when no attacks occur would have to be compared essentially on a world-wide basis with information on "shark attack days." In other words, control data would have to be collected before any cause-and-effect relationship for shark attacks could be revealed. I have already alluded to this in connection with the study of motivation, but the simple fact is that for scientific research, both on shark motivation and shark attack in general, such control data are unavailable and will probably remain so. Yet many authors still attempt to predict shark attacks.

The problem is that attack victims share a number of casual relations with the general population that are entirely unrelated to shark attack. Baldridge[19] provides a clear example: if the majority of beachgoers own Chevrolet automobiles, it is reasonable to assume that the same proportion of shark attack victims will also be Chevrolet owners. A newspaper report stating this fact, (namely that the majority of shark attack victms owned Chevrolets) might be taken out of context and lead the reader to suspect that sharks somehow prefer eating Chevrolet customers or that owning a Chevrolet increases one's chances of being attacked by a shark. Similarly, one can inquire whether the frequency of shark attack is greater above 20°C because there are more potential victims or because sharks feed more actively above 20°C. Both of these hypotheses are plausible but unfortunately untestable (Figure 17).

Turning now to the compiled record and the various situations under which attacks have occurred, it is possible to speculate on the motivational state of the shark just prior to the attack. Nelson[7] has identified four general attack situations. In situation 1, the unprovoked attack, an apparently healthy person is bitten without any obvious distress stimulation being present prior to the attack. When such an attack is carried out by a large shark such as the white, tiger, or bull and significant tissue is removed, the presumed motivation is feeding. It may be further assumed that the shark perceives the victim as normal prey. Baldridge[20] considers the majority of attacks resulting from air-sea disasters on the high seas in the tropical latitudes to be feeding motivated. He suggests that the human victim might simply become nothing more than a prey of opportunity.

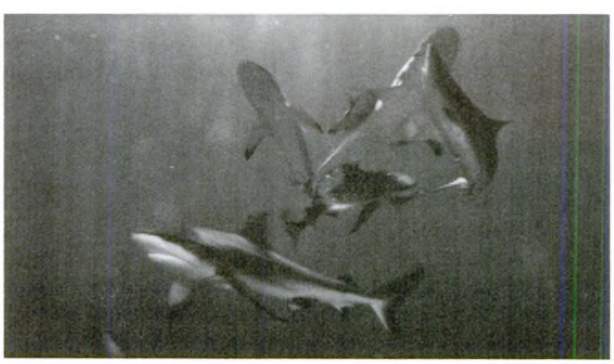
Figure 17

The bull shark. (Courtesy of Doug Perrine)

The air/sea disaster victim usually falls into Nelson's category 2: The unprovoked attack with distress stimuli present. Such attacks are also food-motivated. The shark responds as so brilliantly described by Benchly–to odors, sounds and other cues signaling distress and possibly any easy meal. According to Nelson, strong feeding stimuli will release an opportunistic feeding pattern and even relatively small sharks may attempt to bite pieces from the victim. The presence of abnormally intense feeding stimuli may cause a group of sharks to transcend their usual predatory behavior patterns and enter a state known as the feeding frenzy. During this highly excited, competitive, group-feeding process sharks charge about and bite anything that comes within the range of their jaws (Figure 18). During a feeding frenzy, sharks of equal size are said to attack one another.[21] Thus, in this unusual behavioral state, the superstimulated feeding drive overcomes inhibitions which ordinarily operate to keep aggression between sharks under control.

Figure 18

"Feeding frenzy" by grey reef sharks. (Courtesy of J. Stafford-Deitsch)



In attack situation 2, it is assumed that we know what constitutes distress stimuli. But again, the problem of just how a shark interprets the sensory world arises. For example, the healthiest, undistressed human surfer may well appear to be sick or dying prey to a hungry shark. As Nelson[7] points out, perhaps no human is perceived by a shark as "normal" compared to authentic marine organisms (Figure 19). Thus various authors have suggested (e.g., McCosker[22]) that certain attacks, though feeding-motivated, appear to be examples of mistaken identity. This may be especially so in the case of surfers bitten by great white sharks.

Figure 19

Surfer on a "boogie" board next to harbor seal. Note similarities of the two images. (Courtesy of A. Giddings)

The final two attack situations described by Nelson[7] are examples where feeding-motivation probably plays no role whatsoever. According to Baldridge and Williams[13] up to 75% of the nearly 1,700 shark attacks listed in the ONR supported International Shark Attack File (ISAF) may have been motivated by drives other than feeding. Baldridge[20] calls such attacks "non-foraging aggressions." He lists three general categories where inadvertent provocation by the victim releases an attack:

1. Interference in some phase of reproductive behavior;
2. Appearance of the victim to the shark as a threat or an unfamilar competitive creature perhaps given some disquieting body language or semiochemical signature;
3. Trespass into the permissible spatial limits of the shark in terms of position, approach distance or approach speed.

In these cases the shark is motivated by fear or aggression to launch a preemptive or defensive strike. It is not inconceivable that a reproductively active male shark might mistake a menstruating human for a female shark and court her with a disasterous outcome.

Nelson's final two categories of non-feeding attacks include: 3) The provoked attack with physical contact and 4) that without contact. Contact provocation can result in an attack which may be thought of as antipredatory or self defensive. Nurse sharks, considered to be rather inoffensive are probably responsible for more attacks on divers than white sharks. The ISAF lists 18 attacks on divers by orectolobid (nurse) sharks compared to 11 for the white shark.[19] This unexpected fact becomes easy to understand when one considers that even the most fool-hardy diver would be loath to "tweek" the tail of a white shark, yet some divers think nothing of grabbing the tail of a resting nurse shark and attempting to hitch a ride. Such action on the part of the diver can lead to a contact-provocation attack. Harpooned sharks such as the protagonist in the novel *Jaws* occasionally launch self-defensive, contact-provoked attacks, and a number of these are listed in the ISAF. Thus, it seems that fear motivates the shark under contact provocation. Clearly, from the outcome of such encounters, the attacker did not attempt to consume the victim, but usually tried to escape immediately after inflicting the apparently defensive bite.

The final category, non-contact provocation, was discussed above in relation to the agonistic display of the grey reef shark. In this situation, the victim provokes the shark into perceiving a danger to itself or its resources. Here, a number of non-feeding motivations could be operating. If, for example, the shark were expressing dominance, aggression would be operating. If it were defending itself, perhaps fear would be operating. In either case, these social motivations have little to do with predation or hunting for food on the part of the shark.

Conclusion

So finally we come back to the question of why sharks attack men and women. I must reiterate that we cannot really answer this question in a rigorous way because without experimental control data on shark attacks no hypothesis can be proven to be more correct than any other. Nevertheless, we have made some educated guesses and find that some attacks can be accepted as legitimate attempts by the shark to feed on humans. We estimate that somewhat less than half of all attacks (excluding open-ocean and some other "special" situations) are motivated by feeding or predation. However, the majority of cases where sharks act aggressively against humans are probably motivated by social factors such as fear, aggression or sex and are entirely unrelated to feeding. As Baldridge[20] points out, tissue loss by a victim is nearly always taken as *prima facie* evidence that the shark intended to feed on the victim. Yet the character and extent of the damage and the physical situation of the attack often strongly suggest that other motivating factors are in operation. Since sharks do not vocalize nor do they have any obvious, specialized structures for visual communication, they are often reduced to what Baldridge[20] calls "direct action" for neutralizing threats, establishing dominance or protecting resources. So it is not suprising that when sharks take direct action against fragile humans, the result can be loss of tissue. And depending on the intensity of that action, it is conceivable that the result of an attack motivated by intense aggression might be indistinguishable from that of a frenzied feeder. Thus, according to Baldridge[20] the removal and ingestion of human flesh might well be taken as evidence for the shark's limited capacity to signal fear or aggression rather than *prima facie* evidence for feeding. In any case, it seems that sharks are motivated to attack men and women by all of the big four: feeding, fear, aggression and sex.

Biography

Dr. Samuel Gruber is Professor of Marine Science at the Rosenstiel School of Marine and Atmospheric Science, University of Miami. His research and publications have been primarily in the field of behavioral ecology and physiology, especially with sharks. For nearly 20 years, Dr. Gruber has been a contractor of the Office of Naval Research studying shark behavior.

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Victor C. Anderson

Dr. Anderson has been associated with the Marine Physical Laboratory of the Scripps Institution of Oceanography, University of California at San Diego, since 1947 and has been a Principal Investigator of the Office of Naval Research for many years. He was appointed to the faculty in 1968 and currently is associate director of the Marine Physical Laboratory and Professor of Applied Physics in the Department of Electrical and Computer Engineering.

His scientific research has been in the field of underwater acoustics with a primary emphasis on background noise in the ocean. Ocean engineering is another area of research in which he has been involved. He has had a long-term interest in cable-tethered deep sea instrumentation, with the most recent effort being the development of a new seafloor work vehicle RUM III for ONR. Also he is working on the ONR supported project of developing a seafloor observatory.

Dr. Anderson has served as coordinator for the interdepartmental applied ocean science curriculum program at UCSD and department chair in the Electrical Engineering and Computer Science Department. He is a fellow of the Acoustical Society of America and a member of the Institute of Electrical and Electronic Engineers.

NAVY ARCTIC RESEARCH

by Thomas B. Curtin
Office of Naval Research

Within the Arctic and high latitude regions, the Navy is engaged in research activities ranging from basic investigations focused on further understanding of the environment to applied projects addressing specific problems related to operational systems. These research activities are pursued within a number of organizations. The Office of Naval Research (ONR) supports basic, multi-disciplinary efforts through contracts primarily with academic institutions. The Naval Ocean Research and Development Activity (NORDA), the Naval Environmental Prediction Research Facility (NEPRF), the Naval Research Laboratory (NRL) and the Institute for Naval Oceanography (INO) perform both basic and applied research with emphasis on acoustics, numerical modeling, and remote sensing. The Office of Naval Technology (ONT) together with a number of specific laboratories (e.g., Naval Underwater Systems Center (NUSC), Naval Ocean Systems Center (NOSC), Naval Surface Weapons Center (NSWC), Naval Civil Engineering Laboratory (NCEL)) are involved principally in applied research and development associated with operational systems. This review is limited to Arctic basic research. The relevant activities of the various Naval organizations are synthesized without institutional distinction in order to focus on phenomena and regions of interest and methods of approach.

The overall goal of naval basic research in the Arctic is to develop a comprehensive theoretical and experimental understanding of Arctic processes to provide an accurate knowledge of the environment for naval operations at high latitudes. Naval applications associated with this environmental knowledge base include estimates of sea ice properties, distribution and motion; of ambient noise; of acoustic propagation loss, volume reverberation and ice scattering/absorption; of local ocean turbulence intensity; of ocean currents and sound speed fields associated with fronts and eddies; of wind, wave, icing and fog conditions; of gravity and magnetic anomalies; and of sediment distribution and stability.

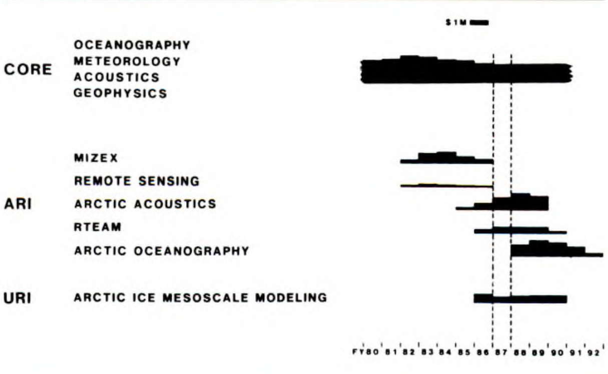
Generic objectives are (1) to determine the temporal and spatial structure of mass, momentum and energy fields within the Arctic system; (2) to understand the order and mechanism of interaction among principal structural components; and (3) to determine the net flux of principal system constituents. Mass includes both inorganic and organic constituents: water (solid and liquid phase), dissolved ionic species, biomass, suspended material, sediments and crust. Momentum and energy include a broad spectrum of motion: acoustic vibrations, turbulence, gravity/inertial/planetary waves, eddies, mean circulation and tectonic adjustment.

These objectives form the basis of investigations into specific phenomena and/or regions of interest. These phenomena/regions are studied from a multi-disciplinary perspective to provide a comprehensive understanding of their statistics and dynamics. Contributing disciplines in order of relative emphasis include physical oceanography, acoustics, ice dynamics, biological oceanography, meteorology, geological oceanography, chemical oceanography and geophysics. Within each discipline, insight is pursued through sampling and modeling supported by a viable infrastructure. Sampling includes remote, interfacial and in-situ sensing with the strategy of determining optimal distributions in time and space. Modeling includes analytical, numerical and physical, with the strategy of formulating essential governing dynamics and estimating event probabilities and resultant statistics. Among disciplines, some infrastructure elements (e.g., computers, platforms, data management systems) are common, and shared use of such resources is encouraged. In general, a balance between sampling and modeling efforts is maintained.

Specific phenomena of current interest include frontal zones such as the marginal ice zone, mesoscale eddies, internal waves, finestructure/turbulence, ambient noise generation, acoustic propagation/attenuation, air-ice-ocean stress, ice strain/fracture, electromagnetic energy-ice interaction, biomass productivity, deep convection, particle flux, and ice-sediment interaction. Specific regions of focus include Fram Strait, Greenland/Norwegian Seas, Bering/Chukchi Seas, Barents Sea and the central Arctic. As described above, a number of organizations pursue research into these phenomena/regions on a continuing basis. In basic research, ONR has by far the largest, most comprehensive program. Since pursuits within this program are representative of the overall Navy Arctic effort, current highlights of the ONR program are outlined here. Investigations for which enhanced funding has been formally identified within ONR are termed Accelerated Research Initiatives (ARI). ARI's are defined to be of five year duration and are established on the basis of scientific merit, technical feasibility/timeliness and naval relevance. Recent ARI's within the ONR Arctic Sciences Program include the Marginal Ice Zone Experiment (MIZEX), Remote Sensing, Arctic Acoustics, Real-Time Environmental Arctic Monitoring (R-TEAM), and Arctic Oceanography. Time intervals and relative funding levels for the Core Program and the ARI's are illustrated in Figure 1. Also included is a singular program element supported by direct Congressional appropriation termed a University Research Initiative (URI). This URI is focused on ice numerical modeling and remote sensing. The objectives and methods of approach for the principal ARI's and the URI are outlined below. Accomplishments associated with core investigations and mature initiatives are documented principally through publications in the reviewed scientific literature.

Figure 1

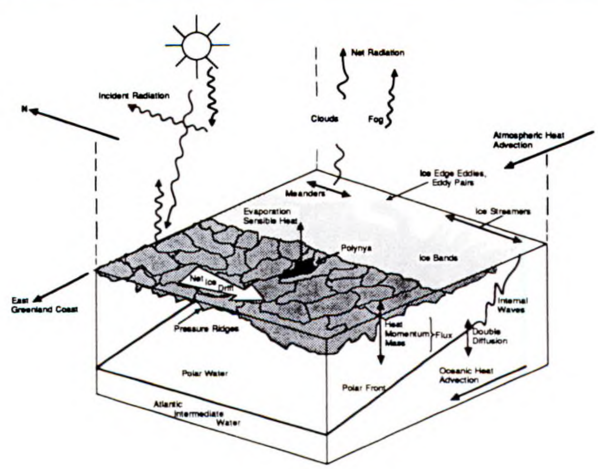
Phases and relative amplitudes of principal funding components in the ONR Arctic Sciences Program.



The overall objective of the MIZEX ARI was to improve understanding of the mesoscale physical and biological processes by which ocean, ice and atmosphere interact in the region of the ice edge (Figure 2). Specific oceanic processes are eddy generation related to shear flow instabilities and forcing related to stress divergence, wind-driven upwelling, fine structure generated by water mass entrainment and mixing, and intermediate/deep water formation. Specific ice processes are flexural disintegration by surface gravity wave action, melting/production determined by radiation and conduction as well as wind/current driven advection. Specific atmospheric processes are boundary layer deepening and vorticity development associated with mechanical and thermodynamic forcing. The main field effort within the ARI was integrated within a larger coordinated, international program marshaling the resources of 11 nations and the expertise of over 200 scientists and technicians. A variety of sampling techniques were utilized from seven ships, eight fixed-wing aircraft and four helicopters. Summer field experiments began in June-July 1983 on a limited scale. The full-scale experiment was conducted in May-July 1984, with a subsequent reduced-level investigation in March-April 1987 to extend coverage over a seasonal range. The Fram Strait region, between Svalbard and Greenland, was selected as the MIZEX site due to its central role in Arctic Ocean Basin exchange.

Figure 2

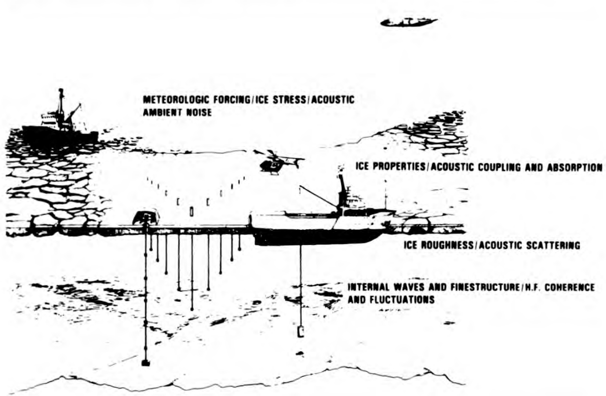
Schematic illustrating phenomena of interest in the Marginal Ice Zone Experiment.



The objectives of the Arctic Acoustics ARI are to relate ambient noise sources with environmental forcing mechanisms, to understand the relationships between the morphology and physical properties of ice and the scattering/absorption losses of reflected acoustic energy, to determine the effect of small scale oceanic density variability on the coherence of sound signals and to determine the effect of the large scale oceanic density field on sound propagation paths (Figure 3). The ambient noise spectrum (1-10,000 Hz) is related to ice fracture and/or ice floe interaction. To determine this relationship, events are being localized using large aperture arrays with simultaneous measurements of atmospheric and oceanic velocity/pressure/density fields and ice moduli/heat flux. Theory for noise generation resulting from these processes is being formulated to predict noise spectral amplitudes and coherence from a knowledge of the forcing fields.

Figure 3

Schematic illustrating phenomena of interest and typical sampling techniques in the Arctic acoustics.



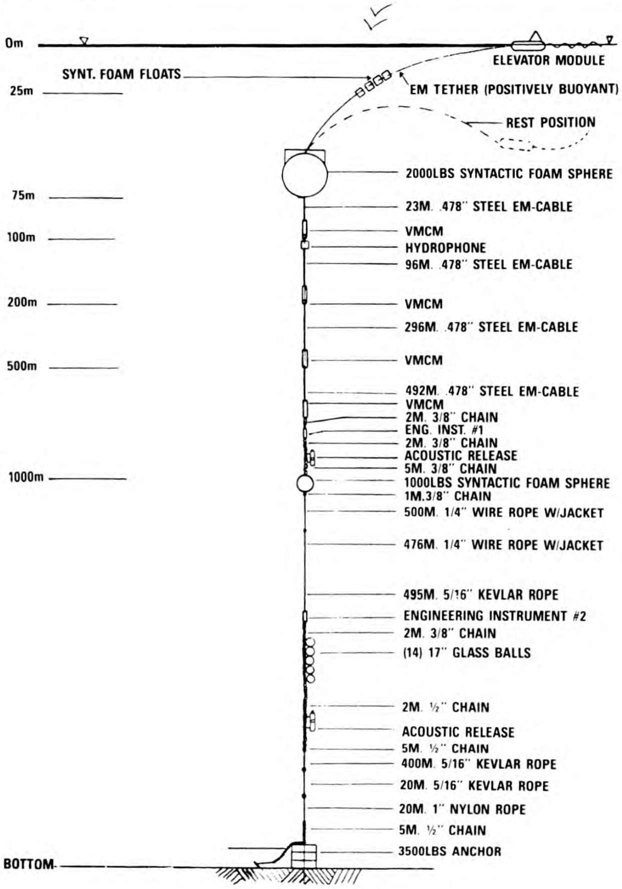
For acoustic energy reflected from ice, the topography of the submerged surface (small scale roughness) may be the dominant attenuation factor at high frequencies (greater than 1,000 Hz) due to direct scattering and local absorption, whereas keel geometry and crack distribution may dominate attenuation at low frequencies (1-1,000 Hz) due to transformation of compressional energy to plate waves. To understand the interaction physics, simultaneous measurements of the ice physical properties, ice roughness, and broadband acoustic reflection/transformation is pursued in-situ, while laboratory modeling seeks to isolate and evaluate specific mechanisms. Beneath the ice, the coherence of sound propagation is affected by oceanic density fluctuation associated with baroclinic currents, internal waves and finestructure produced by diffusion and mixing. To understand the factors limiting coherence, measurements of the internal wave spectrum and hydrographic structure are being incorporated in acoustic propagation models whose output is compared with observed signals. As understanding of the stochastic effects on propagation increases, the inverse procedure will allow effective remote sampling of the stochastic and deterministic properties of the ocean through the use of acoustic tomography.

A sampling program designed to address small scale acoustic coherence formed part of the Arctic Internal Wave Experiment (AIWEX), spring 1985, north of Prudhoe Bay. Ambient noise sensing techniques, low frequency ice reflection measurement, and initial performance of an Arctic Remote Autonomous Measurement Platform (ARAMP) for concurrent acoustic/environmental data acquisition were investigated in an engineering pilot experiment (PRUDEX), spring 1987, also north of Prudhoe Bay. Refinements of these methods will be integrated into a multi-component field experiment in spring 1989 near the Fram Strait marginal ice zone. From September 1988 to August 1989, a large scale tomography investigation will also be undertaken as part of the Greenland Sea Project.

The objectives of the R-TEAM ARI are to determine the low frequency (10 to 90 day) variability in transport of mass and momentum between the Greenland Sea and both the Arctic Ocean and the Barents/Kara Sea, to understand the dynamics of this transport as related to the major constituent current systems, and to evolve efficient sampling strategies for input to predictive numerical circulation models (Figure 4). To determine low frequency variability requires time series data with sufficient range and resolution, here, 360 days and 2 days, respectively. To provide effective sampling for predictive model input requires instruments with near-real-time reporting capability, regardless of surface ice conditions. The combination of these two requirements has resulted in the development of a subsurface mooring system that can telemeter data from a series of networked sensors through an antenna programmed to ascend from a standby depth to the surface at desired intervals usually coincident with satellite overpasses. Field tests of the prototype design were performed in summer 1987, and an operational system will be deployed for one year in fall 1988. The mooring will be located to address the Fram Strait transport objectives while capitalizing on extensive data sets from the several complementary field experiments occurring within the region during 1988-89. Telemetered subsurface data combined with satellite imagery will enable data assimilation techniques and numerical model refinements to be addressed in forecast experiments.

Figure 4

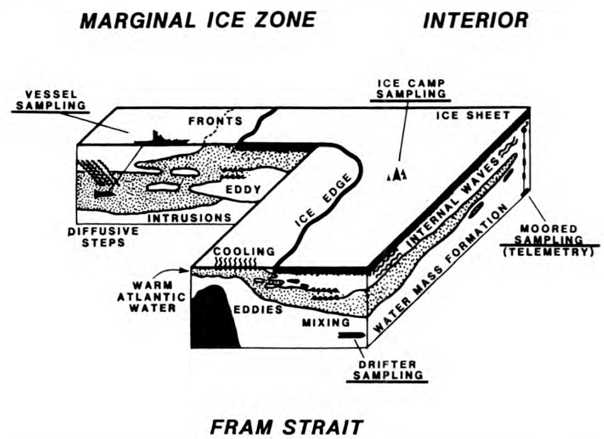
Schematic illustrating phenomena of interest and components of under-ice telemetry mooring under development in the R-TEAM.



The overall objective of the Arctic Oceanography ARI is to understand the role of mesoscale and small scale processes (0.1 hr to 30 days, 0.1 m to 10 km) in the exchange of mass and momentum between the Arctic Ocean and the Greenland Sea (Figure 5). Physical oceanographic objectives focus on understanding the generation/dissipation of mesoscale eddies, internal waves,and small scale mixing and the mechanisms of energy exchange both downscale in governing the distribution of finestructure and upscale in determining the net large scale transport. Biological oceanographic objectives relate to understanding the relative role of physical structure/dynamics and plankton physiology/response in zones of enhanced primary productivity as indicated by biomass concentration, light and sound fields. Meteorological objectives are to understand the atmospheric boundary layer dynamics across the marginal ice zone, including air-ice-ocean feedback mechanisms, and to determine the structure of the coupled momentum flux field.

Figure 5

Schematic illustrating phenomena of interest and sampling techniques in the Arctic Oceanography ARI. This ARI addresses the oceanographic/atmospheric issues within a comprehensive investigation (The Coordinated Eastern Arctic Experiment, CEAREX) that includes a number of acoustic research objectives.



To address the objectives, a comprehensive field effort will be conducted as part of the Coordinated Eastern Arctic Experiment (CEAREX) in the Fram Strait/Barents Sea region. Oceanic and atmospheric boundary layer process and the mechanics of air-ice-ocean interaction over the range of scales of interest will be measured initially from an ice-fast ship drifting from north of the Yermak Plateau through the Fram Strait in fall-winter 1988. The dynamics of the warm Atlantic inflow (West Spitzbergen Current) will be further investigated during winter 1989 in the ice-free region west and north of Svalbard (Whaler's Bay). Winter heat flux into the Barents Sea and associated marginal ice zone process will be assessed, as will the Fram Strait momentum and energy fluxes and biological spring transition associated with both the ice edge and the interior ice pack. In addition to shipboard sampling extensive observations from ice camps, drifters, aircraft and satellites will be acquired. Modeling of observed processes with adequately defined boundary conditions will be facilitated with a number of complementary field programs. Concurrently the international Greenland Sea Project will be focusing on the circulation and water mass generation within the Greenland Sea basin, while the Norwegian Seasonal Ice Zone Experiment (SIZEX) will concentrate on Barents Sea exchange.

Finally, the overall objectives of the Ice Mesoscale Modeling URI are to understand and model (numerically) the dynamics and the mechanics of the coupled Arctic air-ice-ocean system. Specific goals are to properly formulate ice rheology physics by combining large scale with micro mechanical forces, to forecast the mechanical and acoustical properties of sea ice by combining microscale physics with macroscale hydrodynamic model predictions, and to statistically analyze existing remote sensing data to determine the relative importance of forcing functions (wind stress, heat flux, ice keel drag). New generation vector processing computers are a central tool in achieving the overall objectives. Fracture mechanics is providing insight into forces required for ridge formation and polynya development. Micromechanics is establishing a physical basis for understanding crack development and ambient noise. Understanding the local mechanical properties of sea ice allows the properties of individual floes to be specified. Floe-floe interaction can then be treated statistically to determine ensemble behavior. Remote sensing analyses include synoptic-scale and inter-annual variability in ice extent and concentration, the effects of snow melt, the distribution of drafts/leads/polynyas, the variability and organization of cloud cover and the spatial/temporal structure and amplitude of the surface wind field.

The Navy's basic research programs in the Arctic, particularly field experiments, benefit substantially from U.S. inter-service, U.S. inter-agency, and international participation. Cooperative efforts in providing funding, resources, and coordination have made possible significant advances in understanding an environment that is both challenging and remote. Such cooperation is essential for future progress in maintaining the knowledge base that transitions to many Navy, as well as civilian, applications.

Biography

Dr. Thomas Curtin is program manager for Arctic sciences at the Office of Naval Research. His publications and research haved been primarily in physical oceanography of ocean frontal systems. Before coming to ONR, he was on the faculty of North Carolina State University.

RESEARCH DIRECTIONS IN ROBOTICS

by Alan Meyrowitz
Office of Naval Research

Introduction

The overall objective of the ONR basic research program in robotics is to advance the scientific basis for understanding intelligent, sensor-based mechanical systems. Certainly, the deeper problems in robotics span the interests of computer science, mathematics, mechanics, materials, and psychology. From the particular perspective of computer science, however, dramatic progress in robotic capabilities is expected to come about only to the extent that research in robotics is closely linked to research in artificial intelligence. In fact, at the most fundamental level both robotics and artificial intelligence share a common set of basic research issues: knowledge acquisition, knowledge representation, and automated reasoning.

In knowledge acquisition, we look at alternative ways for intelligent systems to obtain the information which they need to do their work. Ideally, acquisition is a process which should occur as a system functions, not just when it is first built and put into operation. In the context of robotics, the robot should be able to learn as it goes about its tasks. There should be a consequential improvement in its performance over time, in the same way that humans are expected to acquire general knowledge as well as specialized expertise in the course of their work.

In knowledge representation, the concern is how best to express acquired information, and how to organize and store it so that it can be accessed and used effectively. As one might expect, different kinds of knowledge demand different kinds of representations. Individual pieces of information may be linked together as elements of a record in a conventional database; may be identified with nodes in a network where links between nodes define important relationships; or may be associated with symbols in formal logical expressions. As we work toward the design of robots which will be mobile, capable of exploring a new environment, and capable of learning in diverse tasks, the choice of representations will be crucial to the effective integration of new information with knowledge already known.

The automation of reasoning, to apply acquired and suitably represented knowledge, is particularly difficult if it is our intent to have robots function in largely unpredictable environments, such as in equipment maintenance tasks undersea, or in space. Although the need to accomplish certain tasks can be anticipated and stated at a very high level, the particular constraints which must dictate the approach to accomplishing those tasks cannot be stated in advance. For example, away from the relatively controlled factory environment the task of inserting a peg into a hole is complicated by the fact that both peg and hole can exhibit a variety of geometric shapes and initial relative positions. Our goal, therefore, must be to provide robots with the controlling software which makes them efficient problem solvers. They must be able to cope on the fly with new problems, and with new variations of old problems.

If there is a distinction to be made between the interests of researchers in robotics and those of researchers in artificial intelligence, it must be emphasized that robots deal directly with physical objects in the real world (as opposed, for example, to expert systems which are presented with problems abstracted from the real world by a human intermediary). Researchers in robotics are therefore addressing the issues of knowledge acquisition, knowledge representation, and automated reasoning with the goal of advancing robotic capabilities for recognizing and manipulating complex physical objects, and for achieving mobility through complex environments.

Technical Issues

Robotics is not a here-and-now technology. Research is motivated by severe limitations in the performance of today's robots. For example, robots cannot participate in the planning of their activities; they must be programmed in detail, or led through specific sequences of motions which they then repeat in a very dumb way. Moreover, they cannot respond intelligently to unexpected events; in fact, their environment must be highly structured (as it is in today's factories). In the more complex, dynamic situations, robots do not quickly recognize and assess the condition of objects either by vision or by touch, and they do not learn on the basis of visual and tactile experience.

These concerns translate into a number of technical issues which are being addressed by ONR-sponsored research: task-level programming, path planning, robotic vision, tactile sensing, and the coordination of multiple robots.

Task-level Programming

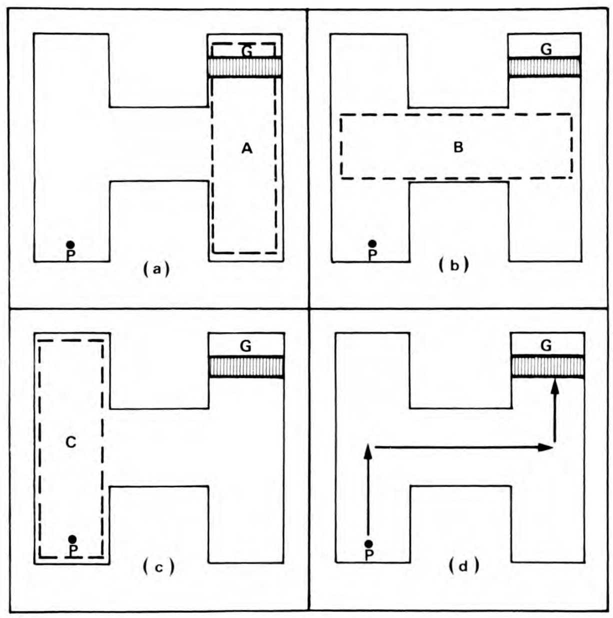
The research area of task-level programming is sometimes referred to as automated plan synthesis. It seeks to enable the programming of robots through the specification of goals to be achieved, without having to specify the detailed procedures for reaching those goals. Ideally, robots should eventually be able to recognize and respond to their own changing goals as they go about their work.

An example of progress in this area can be found in the research of Professor Tomas Lozano-Perez (MIT). He has provided the first demonstration that it is possible to automate the discovery of a sequence of compliant motions which can bring physical objects into alignment (as might be required for parts assembly), and the process of automated reasoning employed is based entirely on the geometry of the objects and the available workspace as perceived by the robot.

The particular strategy employed is that of backward-chaining, a technique for problem solving quite common now in automated expert systems. The idea is to regard the alignment of the objects as a goal state to be achieved, and to work backwards in identifying intermediate states (object positions) which can be reached and from which the goal state is accessible. A simple example is illustrated in Figure 1, which shows the derivation of a sequence of horizontal and vertical motions which can take a point P into a goal region G. Reasoning backward from G, regions A, B, and C are identified (in that order) as desirable regions into which P should move.

Figure 1

Backward chaining. (a) Points providing access to 'G' by a single vertical motion. (b) Points providing access to 'A' by a single horizontal motion. (c) Points providing access to 'B' by a single vertical motion. (d) Sequence of motions providing path from P to 'G.'

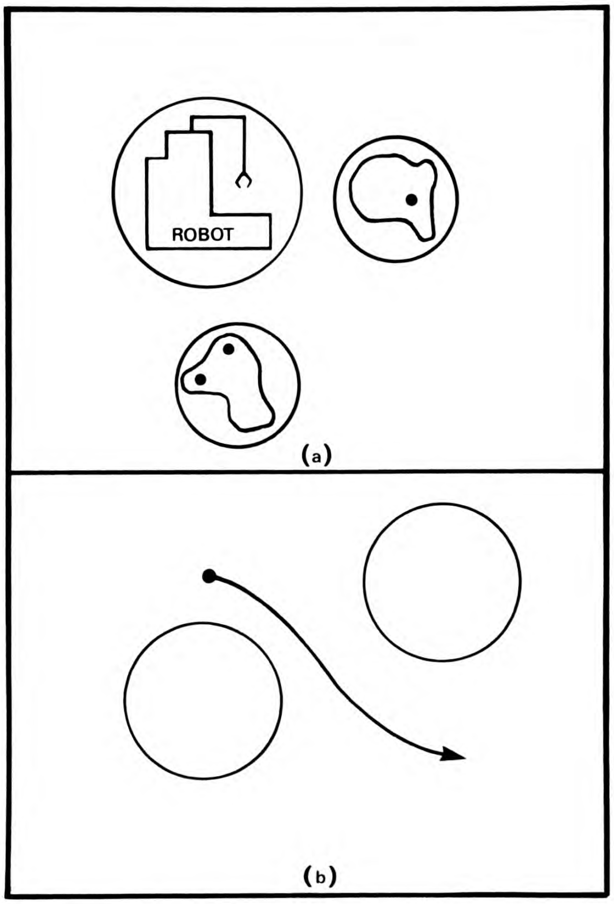


Robots, of course, are not dimensionless points, and the objects which they must manipulate as well as the obstacles which they must avoid as they move are generally of highly irregular shape. One question which naturally arises is how to represent knowledge of the geometry of the robot and its environment so that the computation of motion paths is facilitated. Professor Lozano-Perez has pioneered in exploring the potential of *configuration space* as a way of representing that geometry; the central concept is that of computationally shrinking the robot (or object to be moved) to a mathematical point while simultaneously expanding obstacles in directions conforming to the geometry of the objects shrinking. The original problem of motion planning thus is reduced to an equivalent problem which is more tractable. Figure 2 illustrates the process, where for convenience the robot and obstacles are first bounded by circles (or spheres in 3-space).

The research of Professor Lozano-Perez is continuing to explore the utilization of configuration space as the basis for representing geometric knowledge crucial to solving the more complex problems of robot motion which can arise as robots and objects come into close proximity and contact in activities such as assembly, disassembly, and part inspection during manufacturing and equipment maintenance.

Figure 2

Motion planning in configuration space. (a) Circles bound the irregular shapes of the robot and obstacles. (b) Circle about robot shrinks to a point as other circles expand, creating the configuration space.



Path Planning

A major accomplishment of the ONR-sponsored robotics program has been the general solution to the Piano Mover's Problem, which was provided by the research of Professors J. Schwartz and M. Sharir (Courant Institute). The Problem is formally stated as follows:

Given a collection B of objects and a region bounded by a collection of polyhedral walls, decide whether or not there exists a continuous motion connecting two given positions and orientations of B.

The result of Schwartz and Sharir provided a mathematical algorithm for finding the continuous motion (or path) if one exists. Moreover, they showed that for the special case in which B is assumed to be a fixed collection of linked rigid bodies (which serves as a model for a robot, or a robotic arm), the time required to find the path stays within manageable limits even as the region becomes more complex (cluttered by the addition of polyhedral obstacles and boundaries). Reasoning to solve path planning problems was thus seen to be feasible for intelligent robots, and much additional research has been motivated to seek new path planning algorithms which can take advantage of the geometry of special situations. We have already noted, for example, in our discussion of configuration space, that robots and obstacles can, for computational convenience, be assumed bounded by regular geometric figures.

This consequent concern about the efficient placement and movement of polygons (and polyhedra in 3-space) raises a great many issues in the field of computational geometry. Some of the questions which arise are:

- Given a polygon, where are its geodesic and link centers?
- Given N spheres, do any two of them intersect?
- Can a specified k-gon be placed completely within a given polygonal space bounded by N edges?

It is the case that many of the most efficient algorithms in the literature for the automated solution of these and similar problems have been the result of ONR-sponsored research at the Courant Institute over the last five years.

Research sponsored by ONR at Carnegie Mellon University has also made dramatic progress in advancing techniques for controlling robot navigation through cluttered, uncertain terrain. Dr. Hans Moravec, for example, has pioneered in developing the spatial representations necessary to support the mapping of an environment by a mobile robot. His work has demonstrated as well the feasibility of having a robot navigate in continuous fashion through a cluttered room, aided by rapid, systolic array processing of stereo imagery.

Robotic Vision

Information about objects to be manipulated, or perhaps avoided, must be accessible to the intelligent robot through its sensors. One of the most important tasks which should be supported is object recognition.

When we can predict the set of objects likely to be encountered by the robot, models of the shapes of those objects can be stored in order to facilitate comparison with the shapes of visually sensed objects. Even so, the task can be difficult because of shadow occlusions or overlapping objects. It is thus necessary for models of objects to have detailed information about distinctive boundary features, such as corners or concavities, which can allow recognition on the basis of partial information.

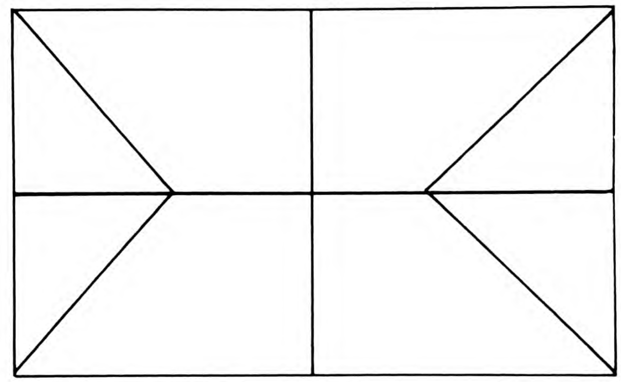
A second task which vision should support is object manipulation. Manipulation requires information of a more global character, such as axes of symmetry. Detection of these axes can be crucial to the robot's achieving a stable grasp.

Ideally, one would like to have a representation of objects which conveys both local boundary features and global features; such a representation has, in fact, been suggested by Dr. Michael Brady (previously at MIT; now at Oxford) and requires the computation of *local symmetries* (points internal to the object and lying on lines equidistant from pairs of points on the observed object boundary). Figure 3 shows the computed local symmetries for the simple case of a rectangle, which yield an internal skeleton. It is important to note that the skeleton has branches indicating the presence of corners (local features important to recognizing the rectangle should only part of it be visible) but also explicitly shows the important vertical and horizontal global axes of symmetry.

Local symmetric representations have the potential for significantly advancing robotic capabilities for model-based recognition and manipulation. Research is proceeding to determine how best to compute that representation for the more irregularly shaped objects with which a robot must contend.

Figure 3

Local symmetic representation of a rectangle.



Tactile Sensing

Tactile sensing must be regarded as much less well understood than visual sensing. Research in tactile sensing is proceeding with a view toward going beyond the use of simple grippers; multi-fingered manipulators are now emerging from academic and industrial laboratories and their utilization will be strongly dependent upon the efficient employment of tactile sensors.

For example, DARPA and ONR have jointly sponsored the design of the novel Utah/MIT Hand, which is based on tendon actuation. Tendons are much less bulky than the motors which might otherwise have to be built into robot joints. This frees up the workspace in the immediate vicinity of the hand and allows for long, delicately jointed fingers. Numerous questions remain to be answered regarding the optimum number of fingers, their proper configuration for special tasks, the possibility of a flexible covering of such a hand with a material having properties similar to those of human skin, and the software control which can take advantage of the many degrees of freedom for graceful and complex movements afforded by the presence of tendons. As far as tactile sensors are concerned, variables still to be investigated include the number of sensors to be employed and their proper distribution over the surface of the hand.

A key problem with tactile sensing is that the data provided are very sparse; points of contact are isolated and ambiguous in indicating what object is being held and what the orientation of the object is with respect to the grasping manipulator. For the purpose of achieving object recognition on the basis of stored models, the ambiguity must be resolved.

Professor Lozano-Perez, whose work we have already cited in the task planning area, has shown the feasibility of distinguishing among a varied collection of polyhedral shapes on the basis of geometric constraints. In grasping an object, for example, the distance between two points of contact, or the angle subtended by normals to object surfaces at contact points, could be the deciding factor in ruling out candidate models during the recognition process.

Much work remains to be done in understanding the use of geometric constraints to distinguish one object from another using a large memory of modeled objects having subtle differences. Possible approaches are to have the robot release an object and then regrasp it in either a random or deliberate fashion in order to obtain additional information, or to slide sensors over the surface of the object in order to detect distinguishing features. The latter approach has been pursued by the research team at the University of Massachusetts, Amherst, where algorithms for visual information processing (particularly those associated with analyses of optic flow) have been adapted to the analysis of data provided by tactile sensors in motion.

Coordinating Multiple Robots

One of the more challenging long-term problems in robotics is to achieve the logical control of multiple systems, i.e., in a multi-robot environment each robot must be able to reason well enough to ensure either cooperation or, if necessary, elimination of interference. Research along these lines is usually pursued under the label of *distributed artificial intelligence.*

It might be argued that in a multi-robot world, the ability to communicate would lessen the need for each robot to be intelligent, i.e., to be able to acquire information from a purely inferential process. However, there are many reasons (military and otherwise) for communication to be restricted and occasionally impossible. For instance, we want to provide for the special case of autonomous underwater robotic vehicles attempting to track an enemy ship or attempting coordination in an equipment maintenance task. Reasons of security, channel capacity, or terrain may dictate a halt to communication at critical times and for prolonged periods.

In order to function in such an environment, robots must successfully model each other's knowledge, beliefs, goals, plans, and possible actions. Numerous subtle and complex problems arise as we try to automate correct reasoning in these areas. One example is found in the differences between formal logical axioms for reasoning about knowledge and belief. A robot having the fact that "X knows the *Nimitz* is on maneuvers" must necessarily infer that the *Nimitz* is on maneuvers, according to common sense usage of the verb *to know.* However, having instead "X believes the *Nimitz* is on maneuvers" allows no such inference, as belief does not entail the logical truth or falsity of that which is believed. So logical systems for reasoning about knowledge in a multi-robot environment are distinct in character from logical systems for reasoning about belief. Some progress has been made in capturing these distinctions and other aspects of common sense reasoning within logical systems. Among the researchers who have been most prominent in clarifying the nature of these kinds of problems and in pursuing solutions as the basis for robotic software have been Nils Nilsson (Stanford University), and Michael Georgeff, Stan Rosenschein, and Kurt Konolige (SRI International).

Future Work

Research to date has only just scratched the surface in exploring the connection between robotics and artificial intelligence. Much remains to be done in creating controlling software for robots which allows for sophisticated problem solving. In particular, robots must eventually be capable of analogical reasoning, and of learning from their problem solving experiences by inductively generating useful new rules of inference which would allow them to show improved performance over time.

Motion planning algorithms have largely been confined to working with two-dimensional representations of the robot's environment. There is a need to extend this work to complex three-dimensional environments such as undersea and space, where robots must contend with obstacles moving in often unpredictable ways.

Continued efforts are needed to enhance our understanding of tactile information processing, and to integrate touch with vision (and perhaps with acoustical signal processing). More dexterous mechanical arms and hands will be needed to serve as testbeds for new approaches to robotic information processing. There is great potential for progress in this area by coupling the efforts of computer scientists with the efforts of researchers in the biological sciences.

Finally, projects should be pursued which explore the full range of possibilities in integrating reasoning, sensing, manipulation, and mobility for advanced robotic systems.

Biography

Dr. Alan L. Meyrowitz is manager of the intelligence systems program in the Computer Science Division of the Office of Naval Research. His research has been primarily in the fields of artificial intelligence, robotics, and image processing. Formerly, he was a computer scientist with the Federal Communications Commission.

NRL Demonstrates First Vacuum Transistor

The Naval Research Laboratory (NRL) is developing a radically new vacuum microelectronic device that is reminiscent of a miniaturized vacuum tube, yet is thousands of times smaller.

Dr. Henry F. Gray, a research physicist and principal investigator for the vacuum microelectronics research program at NRL, states that vacuum microelectronics combines the fabrication, processing, small size and weight, and low-cost advantages of solid state technology with the advantage of ballistic vacuum electron transport.

"The vacuum device is superior to the solid type with respect to saturation velocity and associated transit time," says Dr. Gray.

This new microelectronics technology is ultrafast, ultraradiation hard, temperature insensitive, and very efficient. It can be used for both analog (e.g., medium and high power millimeter wave amplifiers) and digital (e.g., ultrafast signal processors and computers) applications; and for electronics designed to be used in hostile environments.

Although problems remain before reduction practices, these vacuum microstructures show promise as electron sources for microwave and millimeter wave power generation useful in a wide variety of radio frequency (rf) applications. These obvious applications include satellite-to-housetop TV with 12-inch (or smaller) antennas, radars, cellular telephone systems, particle accelerators, and others, says Dr. Gray.

Some of the other applications of the new device, referenced in a paper by Dr. Gray and his staff in 1987, include efficient, high brightness, full color flat-panel displays and television, radiation-hard and temperature-insensitive devices for hostile environments; ultrafast sensors, switches, oscillators, and amplifiers; and high current density, monoenergetic electron sources.

In explaining the applications, Dr. Gray says that the use of the device for flat-panel displays and television would result in displays with very high dynamic range in brightness, crisp and true full colors, high power efficiency, no visual restriction in viewing angle, very high-spatial resolution, simple drive electronics, and less costly than other flat-panel technology.

Applications for the device might also include very thin television sets, computer terminals, automobile dashboard displays, camera eye pieces, radar and sonar screens, aircraft cockpit displays, helmet mounted displays, picture phones, and instrument displays.

"The beauty of this new electronics technology is that it can use metals, high-temperature superconductors, organic conductors, compounds and composites as the active electron conduction material, as well as semiconductors. Standard solid state devices can only use semiconductors" Dr. Gray notes.

Navy-Sponsored Research Develops Biodegradable Plastic

A young man in the celluloid world of the 1960's was advised to invest in plastics (remember "The Graduate?"). It was good advice. It may be again.

Scientists at the University of Massachusetts, working under sponsorship of the Office of Naval Research (ONR), are working with bacteria from marine microorganisms which are capable of producing a biodegradable plastic. The tremendous variety of plastics of interest to the Navy that these bacteria can produce is potentially vast, according to Dr. Thoyd Melton, an ONR scientific officer. This plastic, he says, is so flexible that everything from surgical sutures to bottles can be made out of it.

According to the ONR contractors, Drs. R. Clinton Culler and Robert Lenz, the bacteria makes granules that can be formed into plastic. The same bacteria can eventually devour the plastic reducing it to carbon dioxide and water.

The scientists believe the process will revolutionize the plastic industry. Environmentalists will be particularly pleased by the biodegradable feature, because of their long-standing concern with the extent of pollution caused by non-biodegradable conventional plastics produced from oil.

While it may be too soon to determine the full extent of the potential of this significant scientific breakthrough, the Navy's investment in the study of polymers synthesized by marine microorganisms appears to be a sound one.

Superconductors for the Navy

Superconductivity, the transport of electrical current without energy loss due to resistance, and the devices that use this phenomenon are now leading topics in scientific and technological circles, including the Navy. Once the Navy viewed the extremely low temperatures associated with this phenomenon as impractical for its operations, but today the Navy is viewing superconductivity with eager optimism. The Navy never ignored the possibilities of superconductivity: quite to the contrary. For example, the Office of Naval Research (ONR), since its founding in 1946, has supported superconductivity research.

That year, ONR sponsored two conferences for scientists it supported at universities and in industry who were working in the field of superconductivity. From this meager beginning, ONR became a focal point for much of the low temperature physics and superconductivity research in the United States. Today, it manages some $22 million in Navy and Defense funds in this area.

The interest today stems from the discovery, in 1986, of high-temperature superconductors. This important breakthrough occurred when IBM Zurich reported a material which became superconducting at temperatures as high as 30K(−243C). Soon after, scientists at the University of Alabama and Houston discovered a material which superconducts at 90K(−183C).

These new materials give hope to such forecasts as: trains levitated by magnetic forces; powerful, small and cheap computers; techniques for reading brain cell signals; electric cars; and electric motors which are half the size, weight, and cost of motors today.

The phenomena of superconductivity was first recognized in 1911 when the Dutch physicist Kamerlingh Onnes noted that as he cooled mercury to the temperature of liquid helium (4K) the electrical resistance of the mercury dropped suddenly from a finite value to zero. He concluded that mercury had passed on to a new state, which because of its extraordinary electrical property, he called the superconducting state. Since then scientists have discovered that upon cooling, the zero electrical resistance state can be produced in about 1,000 elements, alloys and compounds, including such common metals as lead and tin, as well as a few exotic organic compounds. The temperature at which material transforms from its normal resistance state to a state of perfect electrical conductivity is called its transition temperature, T_c.

The transition temperature of most superconductors is very low, and because of this, the practical applications of superconductivity have been extremely limited. Over the years, the T_c of newly discovered superconductors has risen very slowly, until recently the highest known T_c was only 23K in the compound Nb_3Ge. Then in 1986, came the news of high-temperature superconductors producing a quantum jump in T_c that will bring revolutionary results to the field, according to Dr. Donald Gubser who heads the superconductivity program at the Naval Research Laboratory (NRL) in Washington, DC.

For the Navy, ONR's long term commitment to low temperature physics has already helped produce ultrasensitive, low noise, magnetic and electromagnetic detectors, electric drive systems currently under evaluation for ship propulsion, and ultra high speed electronic logic and memory circuits, all based on superconductivity. Civil applications include magnetocardiography, magnetoencephalography, and some 600 large supermagnets which are essential components of magnetic resonance imaging systems which are revolutionizing noninvasive medical diagnosis. Other applications include the more than 1,000 supermagnets that guide protons around the four mile circumference of the Fermi Laboratory's particle accelerator and enormous supermagnets for the confinement of plasmas to achieve controlled thermonuclear fusion.

ONR now supports research programs at NRL for developing the new high T_c superconducting materials discovered in 1986 and a variety of processing techniques to further improve their properties. These new materials are made by mixing oxides and carbonates of yttrium, barium, and copper, pressing them into shape, and sintering at 1,000C in a platinum crucible to form bulk samples. The samples are then tested for superconductivity by cooling in a special dewar where the electrical resistance is measured as a function of temperature. These samples are used to test a variety of properties and to understand the materials from a microscope point of view. According to Dr. Gubser, the arrangement of atoms in the materials as well as their high transition temperature suggests that new mechanisms may produce a host of novel physical properties in these materials. He claims that "scientists must reexamine many of their long held concepts about the mechanisms producing superconductivity as well as the materials where it is most likely to occur."

From a technological viewpoint, the new materials will permit applications of superconductivity with much simplified refrigeration systems. Many superconductivity applications will now become technologically and economically viable options for a variety of uses. And in those cases where superconductivity is the only available option for an emerging technology, these new materials will speed the development due to the significant easing of the refrigeration requirements.

These superconductors, with critical transition temperatures above 77K (typical of a liquid nitrogen cryogen or a space environment), have caused the Navy research community to reconsider use of superconducting components and devices. Potential areas for applications of these would include, antisubmarine warfare; antisurface warfare; antiaircraft warfare; and command, control, communications intelligence. Here they may: (a) perform the same function as previously known superconducting devices but at a more easily achievable temperature, (b) perform functions of devices which used older, low T_c materials as above but better, or (c) perform entirely new functions, thus opening a broad array of opportunities for naval warfare systems.

The U. S. Navy has capitalized on its many years of research in superconductivity and materials in rapidly responding to these opportunities. Its current program is directed at both a basic understanding of these new materials and their application.

Global Ionospheric Weather Monitor

Scientists at the Naval Research Laboratory (NRL), headed by Dr. Robert P. McCoy, are developing an optical remote atmospheric and ionospheric sensing system for launch aboard the National Oceanic and Atmospheric Administration's (NOAA's) TIROS satellite in mid-1990. The optical sensors on the NRL system are designed to provide remote sensing of space weather conditions on a global scale.

Dr. McCoy says if the proof-of-concept Remote Atmospheric and Ionospheric Detection System (RAIDS) is as successful as expected, the experiment could lead to future low and high altitude remote sensing satellites that will provide ionospheric weather information similar to what is now obtained from conventional weather satellites.

Remote sensing of the ionospheric weather is of interest to the Department of Defense because a number of operational systems such as High Frequency (HF) communications, Over-the-Horizon (OTH) Radar and HF direction finding depend on propagation conditions within or through the ionosphere. Remote monitoring of ionospheric weather is expected to lead to substantial improvement in Navy and DoD systems that rely on the propagation of electromagnetic radiation.

The NRL RAIDS experiment will have eight optical instruments and will measure naturally occurring airglow emissions for use in remote sensing of the composition of the upper atmosphere and ionosphere. The instruments will be pointed down at the ionosphere to passively observe ultraviolet (UV) emission lines of ions, atoms and molecules above 75 kilometers. The instruments will measure all wavelengths from 50 (extreme UV) to 870 (near infrared) nanometers.

The TIROS satellite will occupy a polar orbit at a height of 870 kilometers. Seven of NRL's instruments will be mounted to a scan platform on the satellite and will be mechanically scanned to view the earth's limb from viewing altitudes from 75 to 750 kilometers. The eighth instrument has an imaging capability and will obtain height profiles without scanning.

Data from these instruments will provide altitude distributions of ion and neutral atmospheric constituents along the satellite track on both the day and night side of the earth. The electron density profile and propagation paths through the ionosphere can be determined from this information. The imaging instrument, which is a far-ultra-violet spectrograph, was specially designed at NRL and uses a 2-D wedge-and-strip detector developed by NRL's Gilbert G. Fritz.

Data from RAIDS will be validated with ground truth observations by ionosondes and radars. The RAIDS database will be used to improve current models of ionospheric behavior and will lead to operational ionospheric-monitoring instruments, notes Dr. McCoy. Future Department of Defense satellites may incorporate RAIDS-like sensors for continual global ionospheric coverage.

RAIDS contains state-of-the-art flight instrumentation developed by NRL in collaboration with the Aerospace Corporation. The RAIDS concept was developed under the Atmospheric and Ionospheric Remote Sensing (AIRS) Accelerated Research Initiative which is sponsored by the Office of Naval Research. RAIDS instrument development is supported by the Air Force Defense Meteorological Satellite Program (DMSP) and RAIDS spaceflight sponsorship is provided by the United States Air Force Space Test Program (STP).

Procedure Developed to Produce Improved Composites

Scientists at the Naval Research Laboratory (NRL) have developed a machine to improve the production quality of metal matrix composites (light metals reinforced with graphite fibers). The device, called "a pneumatic induction fiber spreader," employs restricted air flow to distribute graphite fibers prior to coating them with metal by physical vapor deposition (PVD) to form a thin tape.

Dr. Chulho Kim and Mr. Robert Gray, Jr., developers of the machine, say their research was the outgrowth of the Navy's needs for improved aluminum composites, for use in satellites, aircraft, and other naval systems that require light-weight high-strength materials. (Metal matrix composites have practical application in severe environments because of their low mass density, low thermal expansion, high strength, and high thermal and electrical conductivities.) An additional benefit derived from the pneumatic induction fiber spreader is its ability to fabricate the composite materials at a significantly reduced cost, report NRL investigators.

As the graphite fibers are drawn through a series of enclosures, a vacuum pump forces the air flow through restricted nozzles in one of the enclosures, thus spreading the graphite fiber by means of the venturi effect. The spread fiber ribbon is interleaved with aluminum foil and collected on a second spool. This uniformly spread fiber spool is then transported into the ionplating PVD system to coat the fibers with aluminum and produce the precursor tape which, when plied and consolidated, yields sheet stock of graphite fiber reinforced aluminum. The new NRL method not only improves strength properties but also permits production of sheets as thin as 0.1 mm.

Improved Metallic Meshes Developed

Naval Research Laboratory (NRL) scientists report the development of a photolithographic method that improves the quality of metallic meshes used in far infrared (IR) spectrometers and reflectors.

According to the principal investigator, Dr. Howard Smith of NRL's Space Science Division, the Navy is interested in developing high-technology IR components to improve the detection of hostile aircraft and other heat-emitting targets and to study the IR backgrounds in which hostile aircraft operate.

In the far IR spectral region, the free-standing metal mesh is used to minimize absorption loss upon reflection; and it is important to find a suitable mesh to improve spectrometer capability. Meshes that have been produced in the past have been uneven, nonflat, and were often found with dirty surfaces and without properties essential to maximum efficiency.

Stringent operating criteria, says Dr. Smith, require the meshes to be made to specific, uniform and exacting tolerances. Mesh composition is important to strength and to high electrical conductivity/low absorptivity. The meshes must be made in a clean environment or be capable of thorough cleaning so the radiation "sees" few impurities. They must also work well at cryogenic temperatures.

Originally developed for use as a reflection element in IR interferometers, these meshes may also be used in filters and beamsplitters for optical/IR instruments. As the mesh would make a precise sieve, another possible application would be as a filter for use in microbiology.

In the newly developed process, photographic and microelectronic techniques are used to transfer a preselected pattern into a three-dimensional structure. After a gold grid pattern is produced on a stock silicon wafer, the wafer is up-plated first with nickel, then with a thin layer of gold. The silicon is etched away at the last step to produce a free-standing mesh.

Dr. Smith says his research team is working on this project along with Dr. Martin Peckerar and Mr. Jack Taylor of NRL's Microelectronics Processing Facility in the Electronics Science and Technology Division and in conjunction with Dr. Jacqueline Fischer of the Applied Research Corporation, Landover, Md. The combined research team has been using their method to fabricate highquality metallic meshes for the Fabry-Perot Long Wavelength Spectrometer to be used by the European Space Agency's Infrared Space Observatory (ISO). The ISO is planned for launch by an Ariane rocket in 1992.

New Global Weather Prediction Model Now Operational

A new weather prediction model, developed by the Naval Environmental Prediction Research Facility (NEPRF), a field activity of the Office of Naval Research, has now gone into operational use at Fleet Numerical Oceanography Center. The new Navy Operational Global Atmospheric Prediction System – NOGAPS 3.0 – is a significant upgrade of a previous prediction system – NOGAPS 2.2 – which was developed over five years ago also at NEPRF.

NOGAPS 3.0 computer data is the basis of virtually all the atmospheric and ocean forecasts generated by the Fleet Numerical Center. These include computer models to make regional forecasts of atmospheric conditions, ocean wave and acoustic forecasts, prediction of ice motion and thickness, optimum routes for ships and aircraft as well as numerous tactical applications such as search and rescue, or wind prediction for ballistic guidance and chaff dispersion. These predictions are distributed to Navy regional forecasts center and Navy ships to provide accurate assessment of ever-changing ocean and atmospheric conditions.

The new system makes global atmospheric predictions twice each day by assimilating over 30,000 weather observations gathered from around the world and from both geostationary and polar orbiting satellites. These predictions have proved able to forecast global environmental conditions from the surface to 30 kilometer elevation as much as five days into the future. This provides at least a twenty-four hour improvement over previous forecasting accuracy.

NOGAPS 3.0 combines a numerical prediction model with weather observations to create an ordered description of the momentum and mass of the atmosphere. The numerical model determines the effects of atmospheric processes that are difficult to measure, such as solar and earth radiation, clouds, upper atmosphere turbulence, rain, soil moisture, ground water run off or the effects of mountain ranges.

Development of NOGAPS was funded by the Office of Naval Technology and the Oceanographer of the Navy while basic research on numerical prediction and data assimilation was sponsored by the Office of Naval Research at the Naval Postgraduate School, California. Other contributions came from scientists at the University of California, Los Angeles and the National Center for Atmospheric Research in Colorado.

Tech Base Notes

With this issue, the *Naval Research Reviews* will begin "Tech Base Notes", a succinct synopsis of recent technology accomplishments sponsored by the Office of Naval Technology. The Office of Naval Technology is the Navy R&D organization responsible for the conduct of the Exploratory Development (6.2 Category) of the Navy RDT&E. Exploratory Development programs are conducted in industry, academia and in the Navy's own R&D centers.

Composite Ship Propulsion Shaft Section. Under Office of Naval Technology 6.2 sponsorship, a 50,000 horsepower shaft section has been designed by the David Taylor Research Center and successfully manufactured by the Hercules Aerospace Corporation. The 27 in. (inside diameter) x 33 in. (outside diameter) x 9 ft. long segment is composed of both graphite and glass fibers in an epoxy resin matrix. Following full-scale land-based testing in FY-88, at-sea deployment on a SACRAMENTO Class AOE is planned for FY-90 as a part of program transition to advanced development. The composite shaft technology has a potential both for backfit to existing surface ships and as a baseline on new designs. Benefits of composite design technology compared to current metal shaft systems is a 25% saving in acquisition costs, reduced maintenance costs, at least 50% lighter, and significant reductions in the transmission of machinery induced acoustic signatures.

Tropical Cyclone Prediction: CINCPACFLT tactical and strategic planners have stated a requirement that tropical cyclone forecasts issued for their area of responsibility should have an accuracy of 150 nautical miles (nm) in 72 hours vice the current predictive capability of 350 nm. Impact of the tropical storm seasons manifests itself directly in the disbursement of ships and aircraft to avoid the tropical cyclone threats and indirectly in the maintenance of combat readiness. The Naval Environmental Prediction Research Facility, as a part of it's 6.2 program tasking by the Office of Naval Technology, has developed an improved climatology model which has reduced the error to approximately 250 nm in 72 hours. Real time testing of the model has transitioned to Advanced Development testing at the Fleet Numerical Oceanography Center.

Insensitive Explosive for General Purpose Bombs: An explosive mixture has been formulated by the Naval Surface Warfare Center, as part of the Office of Naval Technology 6.2 program in explosives, that meets all the requirements for munition insensitivity including relating to cook-off, fragment impact and sympathetic detonations. The explosive is based upon the new solid ingredient NTO (nitrptriazol-one) plus other binder components. The program has transitioned to the Insensitive Muntions Advanced Development program where large scale demonstrations will take place. The new bombfill comprises a major advancement in intensitive muntion technology and offers substantial benefits for all the military services.

New Aircraft Tank Sealant. A new class of aircraft sealant compound has been recently developed by the Naval Air Development Center as part of the Office of Naval Technology 6.2 materials program. Advantages of the new sealant include:

Up to an 80% reduction in cure time which impacts directly upon maintenance and repair time delays.

Fly-away time following resealing is less than four hours.

Heat resistant up to 425 degrees F. (vs. existing 360 degrees F.)

10% lighter in weight.

Two-fold increase in shelf life compared to existing sealants. In addition to the benefits for shipboard maintenance and repair, the new sealant is being evaluated by many major airframe manufacturers for production line applications.

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