<u>Now That I Have a Robot, What Do I Tell It to Do?</u>

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Introduction

The development of intelligent machines of all types has made astounding progress in the last couple of decades. It appears that we are to the point where it is possible to draw on a variety of existing, functioning devices to tailor one to a specific set of tasks in mine warfare. The variety of tasks is large, ranging from placement of mines to neutralization and removal in almost any imaginable situation and environment. In many of these situations, it may seem attractive to develop a robotic vehicle to perform the task. However, it is often the case that only a small number of such vehicles would need to be produced. In such cases the *ad hoc* development of a vehicle for a specific task may become cost prohibitive, since there will be so few production units over which to amortize the development costs. In this paper we propose a way to overcome that problem. In fact, we suggest that the "problem" can be converted into an advantage.

We propose adapting a methodology that has been used for many years. This type of analysis has been used in the development of ordnance, particularly nuclear ordnance. The process begins with the development of a "stockpile-to-target-sequence," or STS, sometimes called a "manufacture to employment sequence." The results of an STS analysis are used to derive the design criteria and the test matrix for ordnance systems. It is proposed that a parallel methodology may profitably be adapted to the problem of demining robots

Development of a traditional STS usually began with an analysis of the complete logistic cycle the ordnance was expected to be exposed to. The expected (Normal) environments detailed what the ordnance would have to withstand during storage, handling, transportation, deployment and delivery to the target. The second step outlined the Unexpected (Abnormal) environments that might be encountered, such as a highly acidic chemical environment or a connecting lightning strike. In each normal and abnormal environment, a decision must be made as to whether the item must survive and function; survive and remain safe; or not be required to survive. The robustness of the design, and the required testing to prove it, were completely dependant on the operational environments the unit was required to withstand.

For a robotic deminer, or anything else made in small quantities, costs might be reduced significantly by designing to only the minimum required environments. If a device is to be used ashore, water resistance is much cheaper than waterproofing to 30 meter depth. A piece of field equipment need not be designed to withstand 12 inches/ hour of rainfall if 2 or 3 inches / day will delay the operation and drive deminers to shelter. In each case the probability for mission delay or failure accompanying a less robust design must be accepted.

A robotic vehicle design that is adaptable to a wide variety of situations is possible and desirable. A simple "prime mover" like this can be outfitted with a wide variety of sensors and manipulators. In this way the basic vehicle can be modified to do a proportionately wide variety of tasks. The closer to "snap-on" and "plug and play" the accessories are the easier it would be to modify the device for a specific situation. There have been a number of innovative vehicles proposed and/or developed for mine warfare tasks. Some roll, some walk, some swim, some crawl, and some even fly. Each has a particular characteristic that is most useful in the situation for which for which it was developed. Throughout industry, it is not unusual for a device that was developed for one specific use to be found even more useful in another, when it is modified slightly. (The *History Channel* has even made a regularly scheduled half-hour program[1] from illustrating some of these modifications.) The ability to accept new or modified software would allow tailoring one of only a few basic prime movers to nearly any scenario. The STS prompted questions, applied to a scenario, will define the ideal hardware and software requirements for that tasking. We suggest that there exists a sufficient "pool" of available devices to configure most needed systems, if the right series of questions, guided by the STS process is asked.

The development of a hierarchy of (mostly) operational questions parallels the thought processes used by those few developers of STS documents in the past. Most of those practicing "*Experten*" from the ordnance and nuclear ordnance R&D worlds are old, retired, or have passed on. The adaptation of this methodology would assist in future design of mine/countermine equipment and should result in producing the right tools the first time around.

We suggest that it may be more appropriate to use the STS process in quite a new way. We believe that this methodology can be adapted to permit the cost-effective development of very small numbers of a single design, adaptable specifically to a given situation. The following conditions are current:

A. There is an existing robotic vehicle that can negotiate any terrain of interest, which can carry, or be scaled to carry, any desired payload.

B. There are existing accessory systems, such as manipulators, available for adaptation to the appropriate vehicle.

C. There are existing sensors that can be adapted to the vehicle to provide the information necessary for active decision making.

D. There are existing command, control & communication (C^3) strategies that can be adapted to make a vehicle capable of a particular task.

E. It is possible to so configure the software to make a vehicle capable of a range of related tasks.

In the not too distant past (late 1980s) two of the current authors (Woodfin and Schmidt) developed an STS for a joint Naval Weapons Center, China Lake – Sandia National Laboratories project called the "Advanced Bomb Family (ABF)." That program became the Joint Direct Attack Munition (JDAM), currently a primary munition for Air Force, Navy and Marine Corps. All elements of the logistic cycle were included; the STS indicated environments were used to determine the product specifications, and the required acceptance testing. The success of the JDAM system is due in part to the its design foundation in the STS of its ancestor, the ABF.

For transition from the STS operational and environmental questions to development and testing specifications, a series of military standards s (MILSTDSS) are available. For this process the most notable are the MILSTD 210 and MILSTD 810 series. These list a spectrum of specifications for each environment and a parallel spectrum of tests required for acceptance.

Because they do not have the luxury of using a reasoned STS process to precede design, many demining NGOs are constantly redesigning and adapting existing commercial vehicles do help them work more safely and efficiently. They are forced, like the teams on the *Junkyard Wars* television show, to re-rig the vegetation cutters, flails, rollers and tillers they need to take the burden off individual deminers. These *ad hoc* solutions usually work well where they were first adapted, but have limited ability for use in other areas. However, these innovations form important steps of progress in demining operations.

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[1]*Tactical to Practical*

Better software and more attention by manufacturers to the actual field requirements in their designs will eventually improve these remote systems. The use of the STS/Question process would immediately identify the technical areas that need to be advanced, thereby speeding up the process and adding to industry's bag of tricks.

The Roles and Tasks in Mine Warfare

We can consider these roles from several points of view. Mine warfare includes many types of activity and many kinds of devices. Operationally the spectrum ranges from offensive activities on land or sea to military operations in the presence of mines or suspected mines to civil defense against terrorist devices to post conflict removal of mines and unexploded ordnance (UXO).

When we look at the things that impact equipment design, all Mine Warfare tasks fall into two major categories: Wet and Dry. Most of the design requirements for either surf zone or deep water equipment are much more stringent than comparable requirements for dry land items and are usually more expensive to implement.

Once the wet/dry question is answered, things diverge rapidly into equipment for offensive/defensive mining; countermining; confirmation and location and demining/clearance operations. The equipment required to survey an area and locate mines is radically different from that needed detonate all/any mines along a march route. The only known device adaptable to nearly all scenarios is man; and one man can only sweep one mine.

Offensive and defensive mining are fairly well covered by standoff mechanical means. Aircraft, artillery, missiles, mine scattering machinery, surface ships, and submarines are all capable of planting mines quickly and accurately.

Countermine operations necessary to move troops or vehicles through mined or suspect areas have been worked with varying degrees of success. Ahead thrown charges work pretty well for short distances. Nets and the like are more difficult to deploy

Remote devices that can reliably confirm (99%+) the presence of mines and mark their locations may not be too far off for dry operations. Underwater mammals have been trained to do the same job in small areas of shoal water. Deep water choke points and ship channels are difficult places to reliably locate mines that could be anywhere in the water column or under feet of sand and mud. When high speed coverage is required, the task gets very difficult.

Demining and clearance robots, capable of a variety of tasks under a wide range of conditions, would be a boon to both military and civilian deminers. Some machines are available that can pick up and carry off a device when collateral damage is a problem. These are generally expensive and limited in the terrain they can negotiate. A cheap robot that could locate mines and effect destruction under widely varying conditions would be much sought after. Teleoperated machines are proving useful to NGOs every day.

The answer to most of the problems cited above would be a robotic vehicle that can be adjusted in the field to change both its hardware and software to better fit the local conditions.

Technical Considerations

From a technical point of view, the tasks facing a robotic demining or mine detection system are dauntingly complex. We adopt the position here that it is probably not necessary to design robotic systems that can operate completely autonomously most of the time, but rather that robots should be viewed as an extension of the person or people who control them.

Nevertheless, even when a robot functions merely as the “eyes, ears and hands” of a human, in the context of our problem, it must still be able to perform a dazzling array of tasks.

Communications. Perhaps most importantly, a robot must have a good and reliable communications system. To put this in perspective, consider the recent Mars NASA rovers. The success of the mission depends wholly on communication reliability. Through its communications channels, the rovers can perform system diagnostics, shutdowns and restarts, software uploads and of course report data and receive commands. A mined area is analogous to Mars in the sense that it is, by definition, not possible (or at least highly undesirable) for humans to interact with the robot should something “bad” happen. It is unacceptable for the robot to simply stop responding: continuous and reliable communication is absolutely required. As part of this criterion, an important function of the communication system is something akin to “dead-fault rescue,” a method (perhaps built in hardware) that guarantees that otherwise non-responsive robot will always respond to one high-priority signal requesting it to restart or reboot.

Positioning. Safe to say, this is probably the area most researched in the context of robots and UXO detection. Mobile robots come in every conceivable shape, size and locomotive modality. The recent emergence of swarm theory has led to speculation that teams of robots may be more effective than a single one; whether this is true will probably depend more on sensor size, energy and cost constraints than on the relatively minor technical difficulties of programming a useful swarm-like behavior.

Sensing. Obviously, the sensors carried on a robot make a world of difference in its task effectiveness. While sensors dedicated to the primary task of “finding the mine” are in view here, we also hasten to point out that several other sensor suites are necessary too. For instance, the robot (or robots) must be able to accurately know its position. For large distances, GPS solutions work well. For small distances, the problem is actually more difficult. Dead reckoning does not have the necessary accuracy in terrains that are not flat. Laser, ultrasonic or vision-based position tracking is an alternative, but in these cases it now becomes very difficult to design small robots because of the physical (and technical) constraints imposed by the need to “see” the environment. Sensing also often carries with it huge computational demands. For example, if a robot is moving through heavily forested terrain with a vision system on board, that system will have to be capable of self-localizing, i.e. building an internal map of the terrain as the robot moves, since the controlling human agent cannot see where it is or where it has been. Other sensors important to the mission include self-diagnostic sensors and environmental sensors. (It’s obvious to a human when we’ve stepped into a mud puddle, but not to a robot).

Of the tasks mentioned above, some do not change from situation to situation, such as the communications task. Once a reliable and operational communications method has been chosen, it is likely that it can be used in practically any environment, to a point (of course, a radio system that works on land will not function well underwater). With the broad task categories of “sensing” and “positioning” left, we now reference the idea that good robotic hardware will be somewhat reconfigurable or “plug and play.” In this context, robots will be useful for sensing and positioning tasks that are particularly well suited to replacing humans with some kind of intelligent machine. Four of these types of tasks are

- Tasks that require more strength and more stamina or more sensitivity than a human can provide

- Tasks that are inherently dangerous. The danger may stem from the possibility of unexpected actuation of a mine[2], but it may also come from the local environment or from contamination existing in the area of activity. It may come from concurrent hostile activity, such as enemy fire.
- Tasks that require repetitive activities. Humans and all other mammals are prone to loss of attention, and fatigue, when required to repeat actions over a period of time. The lapses that are produced can induce danger or incomplete work.
- Tasks with restricted access. Some tasks must be done in spaces too small for a human to enter. In some cases enlarging the space may cause unacceptable damage or danger.

In each of these types of activity we can easily imagine a machine that can replace the human without suffering the same limitations on performance or incurring the same risk. Robotic vehicles are used in industrial situations to overcome these same types of human limitations.

The Current State of Robotic Vehicle Development.

To carry out the positioning, or locomotion, task we note that there are a wide array of possible robot configurations, although many (if not most) of these have not been tested or developed for suitability in conditions where mines or UXO are often found.

Wheels and Tracks. Not surprisingly, the vast majority of dry land positioning tasks can probably be accomplished with wheeled or tracked robots. These are by far the most common types of mobile robots, ranging in size from tiny millimeter scales all the way up to automated humvees. The benefits of wheeled or tracked vehicles include simplicity, a routine familiarity to human users, and scalability among others. The drawbacks are associated mainly with environmental factors. Wheels do not work well on slippery surfaces or in littoral environments. Tracks are somewhat better, but suffer from additional hazards like breakage, in which case the robot can be entirely immobilized by one unfortunately placed rock. Wheels and tracks also (except in rare designs) make a robot non-holonomic, i.e. not able to move in any arbitrary direction.

Legs and Whegs. As an alternative to wheels, many robots feature legs. Legged robots have some obvious advantages: they can navigate rougher or steeper terrains, they do not have exposed revolving parts (that could get tangled in vegetation or dig into mud), they often can move the body of the robot in any planar direction and their mechanisms are typically redundant (if one actuator fails, a legged robot is usually able to continue functioning). Their drawbacks are mainly complexity: a single leg unit must have at least two degrees of freedom, usually three or more, and a legged robot needs at least 4 legs, preferably six. It is more difficult to navigate legged robots and they tend to be quite slow to progress, although these aspects are beginning to change as two-legged humanoid robots continue to develop. To gain some of the benefits of legs and wheels, the "wheg" has been explored, consisting of a rotating hub that has several long spokes sticking out. Whegs make for a bumpy ride, but six or more together tend to even out the bumps.

Articulated Locomotion. This idea, explored by two of the authors (Gravagne and Woodfin) in *Mine Sniffing Robotic Snakes and Eels: Fantasy or Reality?*, involves building robots that emulate snakes or eels. Applicable either on land or under water, articulated bodies

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[2] . Implicit within the definition of "mine" is any destructive device that is emplaced with the intent to function later. Note that this is more general than the idea of improvised explosive devices (IEDs). The device need not contain explosives. It may be actuated in other ways, for example for bio or chem agent dispersal.

have several possible locomotive modes and can fit in very tight spaces. Because they maximize the weight-bearing surface area, they would be least susceptible to bogging down in soft or muddy terrains. They are also redundant and can perform several unique tasks, such as crossing chasms, gaps or ditches. Their principle problems are technical. Despite many fine attempts over the past 15 years, snake robots still tend to be bulky and unable to operate over non-planar surfaces. Their field reliability is questionable, and they can only carry sensor suites that are very small, in order that the sensors not interfere with the articulation of the snake body. While redundancy is a desirable feature in general, snake robots require extremely high redundancy (e.g. 20 or more link/actuator pairs simply to locomote). We point out here that hybrid systems, for example snake-like robots with whegs similar to a centipede, may be appropriate for certain conditions, research that is ongoing at Baylor.

Underwater Techniques. Under water, practically all of the same modalities apply, with the benefit that the environment is rather more consistent from site to site. Robots can walk or roll on the bottom, or be made to undulate like an eel or a fish for swimming. Of course, "flying" is also a possibility and both holonomic and non-holonomic modes of underwater vehicle locomotion have been explored.

The Current State of Sensor Development

As mentioned above, in any robotic vehicle sensors provide the information needed for directing the movement and orientation of the vehicle. They may include video and touch sensors, etc. We may refer to these as 'vehicle sensors.' In addition, a vehicle may be equipped with additional sensors needed for a specific function. We may refer to these as 'task sensors.' Clearly, a given vehicle may be equipped with different sets of task sensors as it is employed in different functions.

The current state of sensor development offers many opportunities to provide a robotic vehicle with an orthogonal set[3] of task sensors. A properly configured set can enable the vehicle to make informed decisions or to relay enough information to enable a human controller to do so. Sensors have become much smaller and less energy greedy in the last few years. We can now fit several sensors on the same platform, within the same or smaller weight, volume and energy allocations as for one sensor in earlier generations. This offers some major advantages.

From a single source, the titles of papers presented at the *Fifth International Symposium* here in April 2003, we can find an impressive, though not exhaustive list of sensors. This list includes multispectral thermal sensors, acoustic sensors for underwater and in soil, synthetic aperture sonars, high-frequency seismic sensor, ground penetrating radars, neutron backscattering sensor, electro-optic identification sensors, multi-static sonars, thermal imaging sensors, sub-audio miniature simultaneous magnetic and electromagnetic detection sensor, chemical vapor detection of explosives, timed neutron source detection of explosives and continuous microwaves for detection of explosives. We suggest that an adequate shopping list of sensor technologies is available from which to assemble an effective orthogonal set for any particular mine warfare task.

One orthogonal set that is particularly attractive includes an electro-magnetic metal detector, a trace (or vapor) chemical sensor and a visual, or alternatively a backscatter x-ray or

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[3] We use orthogonal set here, to mean that each sensor in the set provides information that is different from all the others in the set, in thateach exploits a different scientific principle or a different property of the target.

neutron, shape recognition device. It could have other components as well. Three orthogonal sensors would form the minimum desirable set. By properly combining the outputs of these three sensors, it should be possible to make a very good identification of an object.

A Hierarchy of STS Questions that Lead to an Appropriate Intelligent Vehicle

Robotic vehicles have been developed with such a wide variety of capabilities that one should be able to choose a vehicle adapted to most any de-mining task. The matching of a vehicle, including an appropriate sensor suite and/or actuators, to a task, and the specific programming of the vehicle and its payload(s) for the task should result from a hierarchical series of questions asked before design.

It is possible to divide the questions into four fundamental tiers. Tier One questions deal with basic operational considerations, purposes and constraints. Tier Two questions deal with physical requirements; Tier Three, with specific operating techniques and Tier Four, with instructions for the system. Tier Four questions should result in specific (software) instructions, such as what to do when encountering a given situation. For each desired application we envision the process as beginning with a plan for a specific application, or series of related applications. By following this hierarchical structure the planner is able to choose a nearly optimal combination of vehicle, sensors, actuators and instructions for that application. It is suggested that this process will yield much better results than a process that relies solely on the vehicle developer to produce an operationally effective system.

We should begin the process by delineating the requirements of the planned task. This is done by asking the hierarchy of questions. . The hierarchical organization leads naturally to a series of decisions, based on the answers to the questions. A decision-tree-like structure, or flow chart, will naturally develop for each planned system.

This paper attempts to provide only a starting point from which the process may be further developed. Such a structure may have many branches. An attempt to follow all the paths available can easily bring the number of branches under consideration to a half-million or more. Instead, if we follow only the single path indicated by the questions that yield a "Yes" answer for the system being considered, the process is reduced to its essentials. This process directs the planner toward only those issues that apply, reducing the time and effort spent in "blind alleys."

We have begun from the following set of assumptions:

- It is possible to construct a robotic vehicle that can negotiate the terrain of interest, carrying the desired payload, using existing technology.
- The adaptation of the robotic vehicle is for some phase of mine warfare or for the removal of mines or UXO.

Some of the basic questions derive from technology, but many, perhaps most, derive from operational issues, cultural issues, or intelligence based on historical or anecdotal information.

We begin the development of a hierarchy of questions. We have composed these questions in a most general way, merely to present the outline of the method. Ideally, we need questions that may be answered in a way that directs the analyst along a definite branch of the conceptual decision tree. The simplest form is a question that must be answered "Yes" or "No." However, it is often more convenient to choose among a small group of mutually exclusive answers to continue on to the next logical branch. Constructing questions in this manner will reduce ambiguities, opening the possibility of developing an interactive computer-based decision aid.

Tier One questions include the following kinds of considerations:

1. Is this application time critical, as in anticipation of an expected timed detonation?
2. Is this application offensive, in the sense of deploying a munition?
3. Is this application directed toward removal or neutralization of mines or UXO?
4. Is there risk of collateral damage by detonation in place?

It is immediately apparent that a hierarchy is beginning to emerge from these four questions. Several different forms may apply. Questions 2 and 3 are mutually exclusive; only one can yield a YES. Question 1 can follow, or precede either question 2 or question 3. Question 4 follows directly from question 3, but could also follow from question 2. This brief example illustrates the kind of analysis that will result from using this process. Other Tier One questions can include:

5. Is this application in an operationally hostile area?
6. Is the form of the operational hostility military, political, cultural, or religious?
7. Is this application for survey of an area?
8. Is this application for localizing individual mines or UXO?
9. Is this application for neutralizing one or more mines?
10. *Etc.*

As the set of Tier One question is developed, and then answered for the scenario being considered, the general characteristics of the vehicle usage will emerge. There is at this point little idea of the nature of the vehicle itself.

Tier Two questions begin to focus on the vehicle's basic characteristics, but will follow the same procedure in developing the flow. Some examples are:

1. Is this application on land or in water?
   - 1.1. What kind of water?
     - 1.1.1. Ocean floor, buried or in the water column?
     - 1.1.2. River, stream, pond, well?
     - 1.1.3. Irrigation system or irrigated area?
   - 1.2. What kind of land?
     - 1.2.1 Grazing land or savanna?
     - 1.2.2 Roadway, footpath or margins?
     - 1.2.3 Brushland, jungle or forest?
     - 1.2.4. Desert (rocky, sandy, salt or frozen)?
     - 1.2.5. Swamp or marshland?

The general form of breaking down the questions will follow the pattern illustrated above. It can go on to further levels of specificity as appropriate. The following questions have not been developed as far, but should be when applying the method.

2. Is this application in an environmentally hostile area?
3. Is this application to be conducted under enemy fire?
4. Is this application within city, town or village?
5. Is the environment excessively hot, cold, wet or dry?
6. Is the environment contaminated by bio, chem or rad agents or explosives?
7. Is the environment heavily cluttered by debris, plants, artifacts of civilization, etc.?
8. Is the environment producing loads from currents, shocks, vibrations, etc.?
9. Is the environment corrosive?
10. Will the system be subjected to intense electric fields?
11. Will the system be subjected to human or animal interference?

These questions also need to be developed to further levels of specificity. When these types of questions are fully answered the analyst has a reasonably complete understanding of the robustness needed and the type of locomotion best suited to the tasks. The vehicle's size and force characteristics have also been isolated, along with an idea of the type(s) of actuator(s), payload, and, both vehicle and task sensors. These indications are refined by using the Tier Three questions.

Tier Three questions focus directly on the planned system hardware and software. These questions cannot be formed until some of the Tier One and Tier Two questions are answered. Some examples of the type questions in Tier Three are:

1. Should the system be autonomous, under positive remote control, or under intermittent supervision?
2. Is this application requiring geographic orientation?
3. Is the system to report activities in real time?
4. Is the system to collect information and report later?
5. Is the system to be expended, or merely expendable?
6. Is the system to work cooperatively with other systems?

Tier Three and Tier Four questions form the basis for direct engineering design considerations. All too often they form the starting point, with Tier One and Tier Two question being asked later, often after critical decisions have been made. We suggest that, if the questions are asked in the hierarchical order presented here, it will be possible to assemble most needed vehicle systems from existing devices. While we doubt that everything will be COTS, most of the needed components may well available within the community.

We now come to the kind of questions that gave this paper its title. Acting on the previously stated assumption that most of these hardware items are available, or readily adaptable, we offer the suggestion that a library of standard software routines be developed, from which the needed routines can be adapted quickly.

Tier Four questions are directed toward the behavior of the system. Some examples include:

1. Can the robot be programmed to perform a "raster scan" of the area, or should sensor measurement locations be concentrated in some particular pattern (e.g. normal distribution)?
2. Have specific target areas been located where the robot should be directed first?
3. Does the robot need to perform a self-localization procedure?
4. If the robot is working cooperatively, e.g. in a swarm, what is the necessary individual coverage area or density? Should all robots be performing the same task?
5. How often (both temporally and spatially) should the sensor(s) obtain a measurement?
6. If the sensor (and robot carrying it) is large and operating on land, can a smaller scout be sent ahead to explore viable measurement locations and trajectories to get to those locations?

As an example, consider the tasking for a shallow water and surf zone reconnaissance vehicle. If the tiered questions were followed through the decision tree that developed, the process might result in a design for a tracked, waterproof crawler that navigated along the bottom. It might utilize an electromagnetic metal detector, an electro-optical scanner and a chemical sensor to form its orthogonal set for mine recognition. It would likely need feelers for obstacle avoidance and perhaps inertial navigation with acoustic communications through an anchored buoy for operator (semi-autonomous) guidance. It could be programmed for raster scan sweeps within a defined area, reporting results through the buoy. There are a variety of other results that could result from applying the questioning process, as the answers differ for other similar situations. These might lead to a different set of sensors, or a different control scheme, but on the same basic vehicle.

We consider it quite reasonable propose that a computer-aided design and decision aid can be developed to enable a planner to use this process to assemble an effective intelligent vehicle, with little or no new hardware development. Most needed vehicles will be needed in small numbers for specific tasks. This technique could make the process of applying the proper vehicle to the task more efficient.

Conclusions

We have outlined a procedure that has the possibility of making the process of applying intelligent vehicles to mine warfare problems more effective. By its nature, this is a work in progress. Perhaps it is a work that can never be considered complete, since there are likely always new questions that can be added to the process. This paper is based on extensive experience in STS development, combined with advances in intelligent robotic systems and awareness of the emerging suite of smaller and more effective sensors now available. The community needs to use something along these lines to ensure that expensive new hardware and software development produces the right tools at the end of the process.

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