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Author: Paul Chambers

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PHASE II

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Contractor:

Technical Products, Inc.
50 Pratt's Junction Road
Sterling, MA 01564

Principal Investigator:
Paul Chambers

Sponsor:

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THE DERVISH – UNIVERSAL POWER TOOL SYSTEM FOR EOD ROBOTS

PHASE II FINAL REPORT

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EXECUTIVE SUMMARY

ES.1 The Problem

In order to inflict maximum damage to the target regardless of EOD staff intervention IED's are often anchored down or secured to frustrate simple access. The package can be fastened to a person, a fixture such as luggage rack, gas line, etc., that prevents the manipulation, exposure or inspection needed to confirm the presence and nature of the threat, and to insure proper neutralization procedures are followed without causing unintended collateral damage. What is needed is the ability to cut through or into these structures to support inspection, manipulation and movement of the IED.

ES.2 Program Objective & Scope

The purpose of the program was to develop universal tools that will interface with any of the existing common robots such as the Andros series, Talon, Pacbot and Vanguard. The system was to be designed to fit with others as well such as the Pedsco, Mesa and Telerob systems, however these are far fewer in number and kits would be offered only as an option.

This Phase II was a follow on to an earlier effort to develop the 'Double Dervish', a universal tool that could easily adapt to legacy robotic system and that could be used to cut or separate a broad range of materials used in IED operations, a task not possible with conventional hook and line tools. That tool was originally envisioned as having two cutting blades, hence the name of 'Double Dervish'. During the Phase I development that configuration was refined into a single blade design and henceforth it was referred to simply as the 'Dervish'. That simpler terminology will be applied throughout this report regardless of the configuration being discussed.

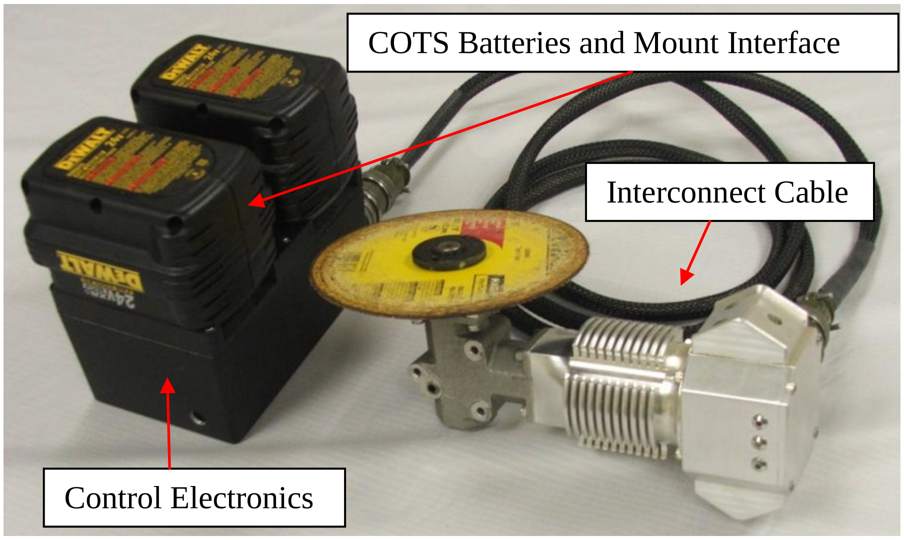
The goal of Phase II of this program was the fielding of a universal cutting tool that would interface with any of the existing common EOD robots.

ES.3 Technology Description

The Dervish is a universal tool system (Figure 1) for legacy EOD robots. The baseline cutter head is designed to cut through cloth, ballistic nylons, mixed textiles with zippers, buckles, zippers or chain, key shanks, and cables; all with a single tool. A shoe-guide prevents damage to the surface, particularly important in hostage or suicide cases. The blade is designed with a closed loop feedback that monitors the current and voltage draw to prevent binding that also minimizes power draw during idle. The idle feature alone extends the battery and therefore mission life by 500%. The anti-jamming feature not only prevents a mission ending lock-up, but also saves the equipment from electrical burnout.

The system actually offers multiple tools (small cutter, large cutter/breacher, drill, and reciprocating saw) that interchangeably mount to a core drive head. The Dervish has been designed with only the tool head mounted on the robot gripper providing a light tip load and low physical profile. The battery and control electronics are located on the robot deck to maintain proper vehicle balance and not impede vision or other robot functions (such as gripper or

disrupter line of fire). The light weight head allows the Dervish to be deployed from the emerging light class EOD robots such as the Talon, PacBot and Vanguard.



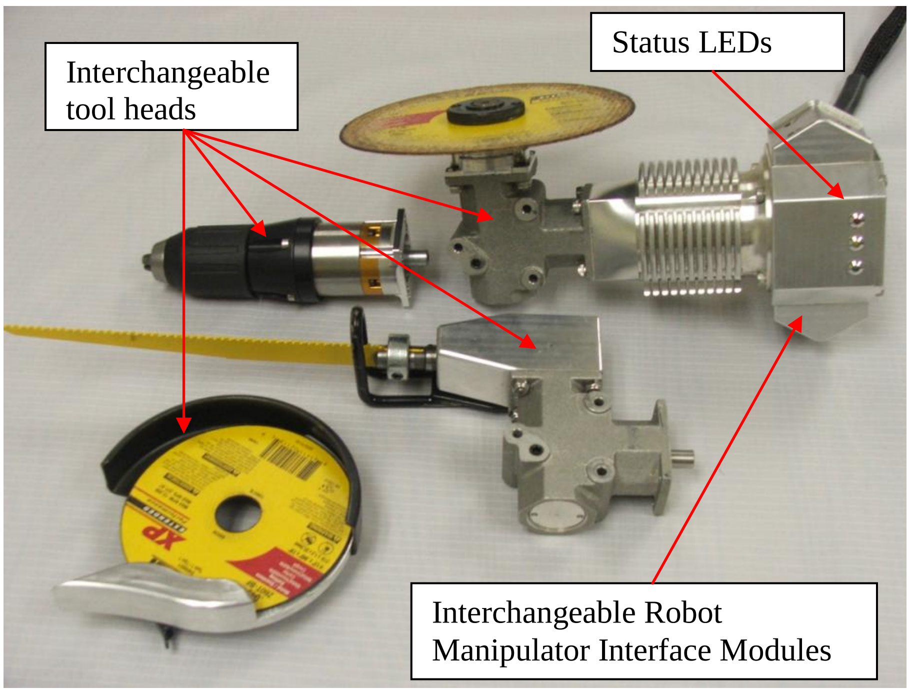


Figure ES-1: The Dervish Is A Family Of Tool Heads That Mount To A Drive Unit With Dedicated Power And Controls.

The Dervish can be turned on by a push switch at the incident site, or activated by hooking into accessory ports found on many robots. The Dervish is otherwise independent of the robot control system and does not require any additional software or control interfaces and it is positioned by the operator using standard controls. Indicator lights alert the operator through the robots existing on-board cameras as to whether the cutter is idling, cutting, or about to stall. If the cutter stalls, it automatically reverses to free itself and then begins again.

ES.4 Phase I Results

The starting point for Phase II was the Phase I Dervish prototype:

- Fits legacy small and large robots
    - Carries own battery power
    - No control software required
- Self compensating control makes operation easy
- Cutter head separate from electronics and battery
    - Light gripper weight
    - Low physical and visual profile
    - Fits small robots
    - Maintains balance
- Doubles as hand held power cutter
- Has safety shoe for operation on humans
- Holds cut-piece in-place
- Cuts mixed materials; tested; 9/32" lock (Master), 3/8" aircraft cable, Hand cuff, tactical vests 5 layers thick; buckles, zippers and Velcro
- Auto-reverse when jamming prevents circuit and battery burnout and eases operator workload
- High efficiency motor, low idle speed; improves mission life by 500%
- Kerf .045", 1-in deep cut, 13,300 rpm
- No sensors to break – sensing done between battery and motor – no additional wires
- Down range bump on-switch
- Head 4.13 lbs; E- box with batteries 6.38-lb; Total 10.5-lb
- 6 ft cable for battery/electronics
- Status indicator lights for supplementary visual feedback

ES.5 Phase II Dervish Enhancements

The following paragraphs summarize the major enhancements made to the Dervish system during this Phase II effort:

- ***Mounting on other robots:*** The Phase II Dervish was designed with the concept of a central power head with modular add-on features to support better mechanical interface to the host platform. At the same time these add-on features were interchangeable allowing the unit to be used with multiple platforms but just not in an 'instant' mode. The Dervish is thus configured as a common cylindrical power module onto which are added platform specific mounting interfaces. TPI configured the Dervish to work with multiple demonstration platforms. Specifically we configured deliverable units optimized to work with the by Black-I Robotics Landshark and the Remotec Andross and in a limited mode on the Foster-Miller/Qinetiq Talon (Figure 2).

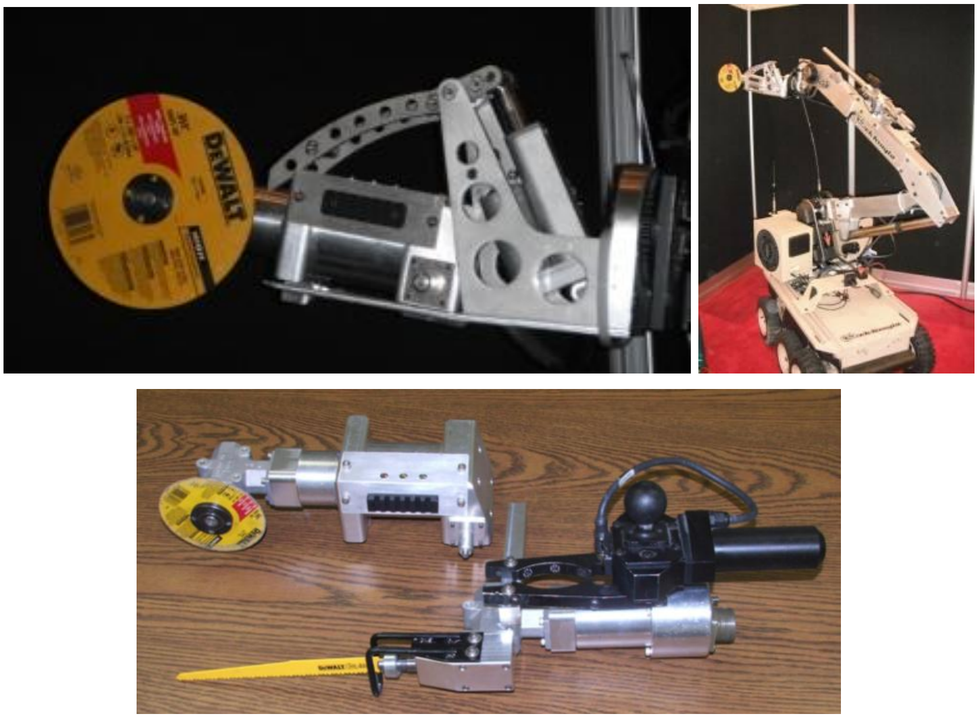


Figure ES-2: The Dervish Power Module Was Fitted With Adaptors To Match The Landshark Manipulator (top), Talon (bottom left) and Andross (bottom right).

- ***Ability to switch out tool heads:*** The basic control capability offered by a tool with closed loop feedback is a useful one, and there has been interest in switching out the heads depending on the mission. TPI's approach was to use the basic Dervish power unit with its intelligent controller and highly flexible power system and to develop a family of easy-on/easy-off tool heads. The operator could select from a small (4 1/2") cutter, a large (8") cutter/breacher, a drill, or reciprocating saw, install the tool onto the power head and then deploy the robot down range.

- ***Switchable batteries:*** After a review with the user group it was decided that a COTS battery based approach would be preferred as it provided the most flexibility for battery replacement while allowing sufficient cutting time for most missions. The option of using multiple batteries (2-3) in parallel to provide longer cutting time addresses mission life concerns and is an easy field connectable option. With this in mind then TPI rehoused the tool interface used with a high end COTS battery (the DeWalt 24-V unit) onto the top panel of the Dervish electronics box so that the COTS battery merely slipped onto as if it were connecting to a tool. As shown above in Figure 1 we actually configured the unit with two battery interfaces to maximize cutting time. This approach was applied to the second Phase II Dervish variant. This approach also allows the user to utilize standard chargers.

- ***Ability To Drop Off, Pick Up Cutter:*** A major goal of this development is the ability to use the cutter, drop it on the ground and then pick it up again so that the gripper could do other functions without needing to drive back to the command point for a tool change-out. The ability to drop off and pick up the tool will be directly affected by the design of the tool handle. This feature is currently a function of 'generic' gripper characteristics, integration of the control switch, and to resist tool generated torque during use. In the first Phase II Dervish the handle has a simple ellipsoid cross-section as seen in Figure 38. This allowed any multiple finger gripper to hold the tool. If the tool is 'dropped' or placed in an on-board holster then the gripper should be able to pick it up again for a second cut. The second design variant actually incorporates platform specific gripper interfaces that ease this gripping task.

- ***Door Breaching:*** Door breachers mounted to EOD and tactical robots have been demonstrated before on OEM robots but the tool has not been implemented in the modular Dervish fashion. The action is the same as the double Dervish and the control algorithms will be directly applicable. The cutter wheel however will need to be increased in diameter, and a higher torque motor may be required. Present cut depth is limited by the wheel diameter to 1-in. For breaching a 3-in depth of cut would be required. A new higher torque motor operating at higher voltages has been selected to support this tool and the latest Dervish variant has been fitted with a larger (8-in) breaching wheel.
- ***Better Bump Switch:*** We explored implementation of different switch options.
  - Hardened 'Bump' switch mounted on tool – robot hits tool against wall, ground, chassis to start/stop tool
  - 'Whisker' switch mounted on platform – robot hits whisker with arm to start/stop tool
  - Proximity switch – robot moves flag close to switch to start/stop tool.

  The other option which will work with some platforms but not others is to tie into the onboard control electronics and to have the Dervish switched from the OCU – an option available on the Andros platform. This feature has not been finalized pending user evaluation and imnput.
- ***Swivel Guard:*** Presently the guard is manually fixed before the mission. We reviewed the option of a sliding shield similar to a circular saw (Figure 48). This improvement is really only of value when Dervish used as hand tool but complicates remote cutting operations since it requires correct orientation and fairly precise positioning of the edge of the guard relative to the target. This option was not pursued further.
- ***Useability As A Hand Tool:*** Some of the operators liked the idea of being able to use the cutter as a hand tool. With the electronics and battery box tethered the 'in-hand' tool weight is minimal. While the ergonomics of either of the two Dervish variant bodies are not optimized for hand use they do allow occasional, short term by-hand use.
- ***Aiming Guides:*** Aiming guides on the guide shoe and cowl will give the operator visual reference points observable through the standard video system on the robot platform of where the blade is and where the contact tangent is for easier control. This option was not evaluated in this project but would be a fairly easy modification in next generation units.
- ***Motor Cowl:*** A more rugged housing was needed than the Phase I configuration to protect the system and wiring. This mechanical detail was driven in part by the final selection of the motor and the mounting configuration. The Phase II system configuration is much more rugged than the earlier housing.

- ***Higher Torque Motor:*** A new high power motor (Figure 52) was selected. It provides more power than the previous motor at 24V and will operate all the way up to 48Volts. It comes with a 2.75 to 1 gear reduction. This provides for 4400 rpm @ 48V and 80 in-oz of torque as opposed to 17500 rpm @ 18 V and 25 in-oz of torque provided by the original motor. The higher torque allows that more pressure be applied to the cutter without it stalling.
- ***Lighter Cutter Head:*** The major weight contributors to the cutter head are the motor/gearbox and the ruggedized housing. The mission drives the power pack design so assuming a similar mission for the small robots as the large that item cannot easily be changed. If we need to support Pacbot and Talon sized platforms then the brackets, shields and housing need to be lightened up. The overall system weight can probably be reduced by 25% at some reduction in ruggedness.
- ***Control Via Encoder:*** The present system uses the back-generated voltage to monitor blade speed which is desirable because it does not require any sensors, The problem is that as the motor gets hot the amount of back generated voltage changes and so the threshold is essentially changing. If an independent shaft encoder like a Hall effect sensor is added, the control would be rock solid. The issues here are cost, wiring and control complexity. The encoder needs power and signal lines run to connect it to the electronics box. We need processing hardware and software to interpret the output and generate a corresponding control algorithm for the drive system. While a more sophisticated approach the complexity may not be warranted. We have not seen the need for better control during our testing but if after user trials this deficiency is indentified it can be corrected in next generation units.
- ***Auto Reverse:*** Even with the cutter power/torque feedback the potential still exists for the cutter disk to jam in a fabric or other target material. This stall effect will very quickly drain the battery and could result in permanent damage to the motor and controller. TPI developed and integrated an auto-reverse functionality into the device controller whereby if it jams and stalls it automatically reverses to extricate the blade from the material then reverts back to forward to allow the operator to continue cutting.
- ***Status LEDs:*** The status LEDS that, in Phase I were mounted on the electronics box were moved in Phase II to the rear of the actual cutter assembly so that they can be observed through the platform, cameras.

ES.6 Summary Of Phase II

In Phase II of the Dervish program TPI successful achieved the objective of enhancing the Phase I device and maturing it into a system ready for significant user trials. The Dervish as now configured offers the user great capability to manipulate down range structures and items in an efficient flexible manner. The user can cut, saw and drill targets with a platform independent highly operationally flexible device. That device will not jam and can be tailored to multiple platforms and missions.

Dervish component weights are:

- Controller Electronics – 2.5-lb
- Drive Unit – 2-lb
- Cutter Head – 1.75-lb
- Saw Head – 1-lb
- Drill Head – 3-lb
- Cable (6-ft) – 2-lb
- Battery (24-v, 10-Ah) – 10.5-lb
- Platform mount adapter – 1-2-lb
- Total Arm end weight (Drive + Tool + Adapter) = 4-7-lb

ES.7 Post Phase II Development

While the Phase II Dervish device discussed above worked well and demonstrated the capability to meet the minimum performance required of it, it suffered from three limitations that would detract from its 'marketability':

- it was a mechanically complex device to assemble (which translates into cost)
- it was marginal at performing hard cuts requiring high power draws over an extended period
- the design did not scale well between a larger high capacity device for large robots and a smaller, potentially lower cutting capacity system for small platforms

Since the development of a product that would be adopted by the user group was the overarching goal of the program, these issues were of concern to TPI. In order to better 'productize' the Dervish TPI undertook the development of a third generation system.

The major change implemented was the selection of a new motor/main drive system. The motor used in Phase II was not IP rated and hence required an external housing for protection from the environment. This double housing can generate problems in extreme environments with heat buildup necessitating incorporation of a cooling fan. In addition the Phase II unit required separate drive/control electronics which were housed within the battery/electronics unit. The Phase III drive system (Figure ES-3) has its controller integral to the motor housing which itself is specifically designed to manage the internal heat load under the most arduous conditions. The new motor selected for the Dervish has significant more power than the earlier units (205-oz-in of torque compared to 80-oz-in) while offering the advantage of being IP-64 rated (sealed against dust and water spray). In this Phase III configuration we committed to targeting the larger robot platforms, with their increased manipulator capacity, for the Dervish. This allows us to maximize the performance of the system in terms of cutting without having extreme limitations on tool weight. This current high power Dervish has a tool head weight of 9.5-lb.

Another major advantage is that the motor configuration lends itself to adaptation to the various EOD robot platforms via simple add on modules that bolt around the motor and provide 'hold' points as applicable to the specific platform and manipulator with which it will be used. All configurations can be used with any of the tool options (Figure ES-4).

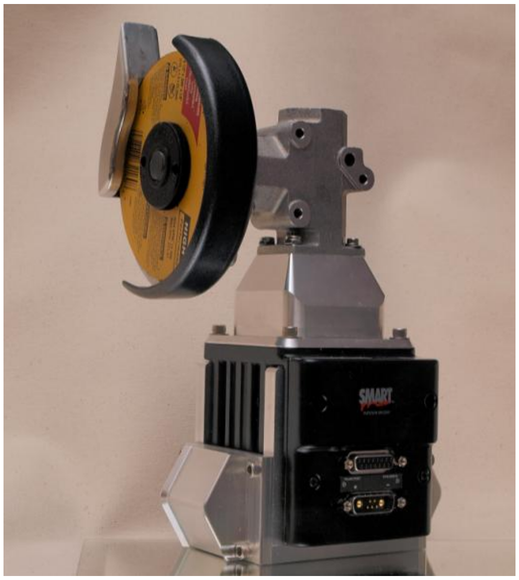


Figure ES-3: The Phase III Motor Offers More Power And Integral Controller Electronics In An Environmentally Sealed Housing With Excellent Heat Management Designed In.

Figure ES-4: Whether Configured For Andros (Left), Landshark (Right) Or Any Other Platform The Dervish Can Be Fitted With All Tool Options.

One of the other major advantages that this generation of motor offers over the earlier versions is the sophistication of the controller. The system run parameters can be set up via laptop with different speed, load response etc functions for each tool option (small disk, large disk, reciprocating saw, drill). The operator can then specify which tool is installed via a rotary selector knob on the battery/electronics box. Similarly to the earlier versions then, the controller will manage the system performance but in a tool specific regime:

- cutter idles under no-load conditions, upon power-on
- when load is applied to cutting wheel, the cutter automatically switches to maximum speed/power
- if the load is removed, the cutter returns to idle speed
- if the cutter jams, it will switch to full-power-reverse mode, and then return to full-power-forward
- built-in voltage guard, will turn off cutter before batteries are damaged

Since the control electronics are integral to the motor housing the size of the battery/electronics unit (Figure ES-5) has been reduced significantly compared to the Phase II system.

Figure ES-5: The Battery/Electronics Box Has Shrunk Considerable From Phase II And Incorporates The Simplistic Operator Controls.

The Phase III Dervish described above addresses all three limitations identified for the Phase II system:

- Complexity. The new design utilizes a COTS motor with integral controller electronics housed in a thermally self- managed IP-64 rated housing and which lends itself to simple integration with modular robot manipulator interfaces.
- Power. The Phase III Dervish easily defeats any reasonable target and the integral smart power controller minimizes power draw while ensuring maximum availability of power and protecting itself against damage occasioned by jams.
- Scalability. Simple motor replacement can significantly reduce system weight (with concomitant reduction in performance) while maintaining all control sophistication.

TPI is currently building several variants of this third generation Dervish for delivery. Our NIJ sponsor will be receiving two units configured for the Andros robot and one for the LandShark platform. RE^2 Robotics, Pittsburgh PA, will be receiving a unit configured for their generic manipulator arm fitted with the family of quick release tools.

Continued development of the Dervish system by TPI with a function of the level of market response.

THE DERVISH – UNIVERSAL POWER TOOL SYSTEM FOR EOD ROBOTS

PHASE II FINAL REPORT

1. Technical Background

In order to inflict maximum damage to the target regardless of EOD staff intervention IED's are often anchored down or secured to frustrate simple access. The package can be fastened to a person, a fixture such as luggage rack, gas line, etc., that prevents the manipulation, exposure or inspection needed to confirm the presence and nature of the threat, and to insure proper neutralization procedures are followed without causing unintended collateral damage.

Common concealment methodologies include vests, packages or backpacks that can be either chained or handcuffed into place (Figure 1). The challenge was to provide a cutter that can cut textiles as well as clasps, buckles or security wires or chain. Blades that work well on hardened materials gum-up, dull and jam on textiles. Our solution was to compromise slightly on single material specific performance but provide a good universal performance and to provide a closed loop control to back off and reset when jamming becomes imminent. But cutting material was not the only issue. Logistics and compatibility with legacy systems were equally critical. The newer smaller class of robots are agile but they do not have the power to handle the larger extraction tools. Also, as bombers become more sophisticated response time must be minimized so as much action must be performed down range on a single pass as possible.

Figure 1: The Dervish Allows For Removal Of IED From Whatever It Is Mounted To Without Damaging That Substrate.

This Phase II was a follow on to an earlier effort to develop the 'Double Dervish', a universal tool that could easily adapt to legacy robotic system and that could be used to cut or separate a broad range of materials used in IED operations, a task not possible with conventional hook and line tools. That tool was originally envisioned as having two cutting blades, hence the name of 'Double Dervish'. During the Phase I development that configuration was refined into a single blade design and henceforth it was referred to simply as the 'Dervish'. That simpler terminology would be applied throughout this report regardless of the configuration being discussed.

The initial focus in Phase I was specifically on separating suicide bombers or hostages from a worn explosive device and that would require cutting or separating cloth, vests, zippers, ties, and confounding wires or light chain. After success with these materials, the design was extended to cut chain, steel cable and locks and common chain link fencing that might be used to fix an IED in place. The system was designed with a minimum of interface controls; partly due to the limited capability of legacy robots, partly for the sake of overall simplicity and reliability and primarily for platform flexibility. Since robot manufacturers consider their control systems proprietary the Dervish was designed to act completely independent of the robot design and in fact could be used as a hand tool.

1.1 Objective

The purpose of the program was to develop universal tools that would interface with any of the existing common robots such as the ANDROS series, TALON, PACBOT and Vanguard (Figure 2). The system was to be designed to fit with others as well such as the Pedsco, Mesa and Telerob systems, however these are far fewer in number and kits would be offered only as an option.

Figure 2: The Goal Is To Develop A System That Will Work With All Legacy Platforms.

The only real need for external control would be wheel selection, the feed rates and on/off. The system was designed with a passive and independent force feedback control loop that balances the cutter wheel rotational speed as a function of current draw (which in turn was related to the resistance of the material and the feed rate) to prevent jamming. Auxiliary positioning could be achieved by additional tilt and translation linear motors as an option and the necessity for this feature would be determined during field trials. Most robot arms do not have a linear feed mechanism and act off of pivot points which result in arced movement of the robotic arm tip. Linear actuation can be incorporated for those models that require it.

1.2 Technology Description

The Dervish is a universal tool system (Figure 3) for legacy EOD robots. The baseline cutter head is designed to cut through cloth, ballistic nylons, mixed textiles with zippers, buckles, zippers or chain, key shanks, and cables; all with a single tool. A shoe-guide prevents damage to the surface, particularly important in hostage or suicide cases. The blade drive system is designed with a closed loop feedback that monitors the current and voltage draw to prevent binding that also minimizes power draw during idle. The idle feature alone extends the battery and therefore mission life by 500%. The anti-jamming feature not only prevents a mission ending lock-up, but also saves the equipment from electrical burnout. The system actually offers multiple tools (small cutter, large cutter/breacher, drill, and reciprocating saw) that interchangeably mount to a core drive head. The Dervish has been designed with only the tool head mounted on the robot gripper providing a light tip load and low physical profile. The battery and control electronics are located on the robot deck to maintain proper vehicle balance and not impede vision or other robot functions (such as gripper or disrupter line of fire). The light weight head allows the Dervish to be deployed from the emerging light class EOD robots such as the TALON, PACBOT and Vanguard.

Figure 3: The Dervish Is A Family Of Tool Heads That Mount To A Drive Unit With Dedicated Power And Controls.

The Dervish can be turned on by a push switch at the incident site, or activated by hooking into accessory ports found on many robots. The Dervish is otherwise independent of the robot control system and does not require any additional software or control interfaces and it is positioned by the operator using standard controls. Indicator lights alert the operator through the robots existing on-board cameras as to whether the cutter was idling, cutting, or about to stall. If the cutter stalls, it automatically reverses to free itself and then begins again.

2. Phase I Program

The following sections describe the efforts previously performed on Grant No. 2007-MU-MU-K021. This effort acted as Phase I of the dervish development with the contract being reported on in this document effectively being Phase II. The purpose of Phase I of the Dervish program was to explore, develop and test a powered cutter attachment that would fit on legacy robots common to the law enforcement community. The purpose of the cutter was to bring the capability of cutting mixed materials such as cables, chain sheet metal, and cloth onto small EOD type robots. Present techniques include draw knives but they are limited in cutting capability, and tend to be single action operations which are slow and cumbersome. Line tools also have limited ability to cut through heavier steels. While some powered tools are under development, they are heavy, and power hungry with very limited mission life. The goal here was to develop a universal tool that would fit legacy robots commonly fielded within today's law enforcement community.

2.1 Phase I Goal and Objectives

The purpose of this research was to develop a system that can easily adapt to legacy robotic system and that can be used to cut or separate a broad range of materials used in IED operations not possible with conventional hook and line tools.

The initial focus was on developing a tool set that would be capable of cutting or separating cloth, vests, zippers, ties, and confounding wires or light chain used specifically on human borne IED such as suicide or hostage bombs. With growing confidence in the capabilities, the design was extended to cut chain steel cable and locks and common chain link fencing that might be used to fix an IED in place.

The system was designed with a minimum of interface controls; partly due to the limited capability of legacy robots, partly for the sake of overall simplicity and reliability and primarily for flexibility as more robot styles enter the law enforcement inventory. Modern military systems are designed around a common software architecture called JAUS that would cross vehicle control compatibility simpler, but within the law enforcement community they are rarely, if at all found and the Dervish was designed independent of these encumbrances. Since robot manufacturers consider their control systems proprietary the Dervish was designed to act completely independent of the robot design and in fact could be used as a hand tool.

During the initial kick-off meeting it was decided that the focus of the development for the most common fielded robot with law enforcement which was the ANDROS series of Remotec systems. The advantage of the ANDROS series was that they have more degrees of freedom at the tip, considerably more power at the arm joints, better viewing, and view flexibility through their camera positions, and typically there are simple fire spare circuits available for on-off control.

While the system was designed for the ANDROS, it was recognized that the lighter and more nimble TALON and PACBOT class robots were making their way into the law enforcement community. The Dervish design therefore was to consider the more limited deck space and arm capacity so that it could be made compatible without major redesign.

2.2 Phase I Results

The need for a simple and universal tool was clear, but the specifics of what features it should have, tasks it ought to perform, and design philosophies it should incorporate were not well defined. In particular factors such as simplicity, ruggedness, compatibility with other tools, component cost and system cost versus performance had to be understood and balanced. Since the program was essentially breaking new ground, it resulted in several design iterations.

2.2.1 Requirements Definition & System Specifications

The Phase 1 kick-off meeting clarified the robot interface priorities. By focusing on the legacy ANDROS systems, many of the interface issues can be locked down and controlled. Interfacing with other systems would only be simpler later on since they have been designed for universal attachments. To this end TPI has met and worked with the MA State Police bomb squad who have graciously allowed us to examine and trial their units (Figure 4) as it would interface with the Dervish. TPI has also contacted Northrop Grumman/Remotec and held discussions on electrical, mechanical and control interfaces and possibilities of including it in their product line.

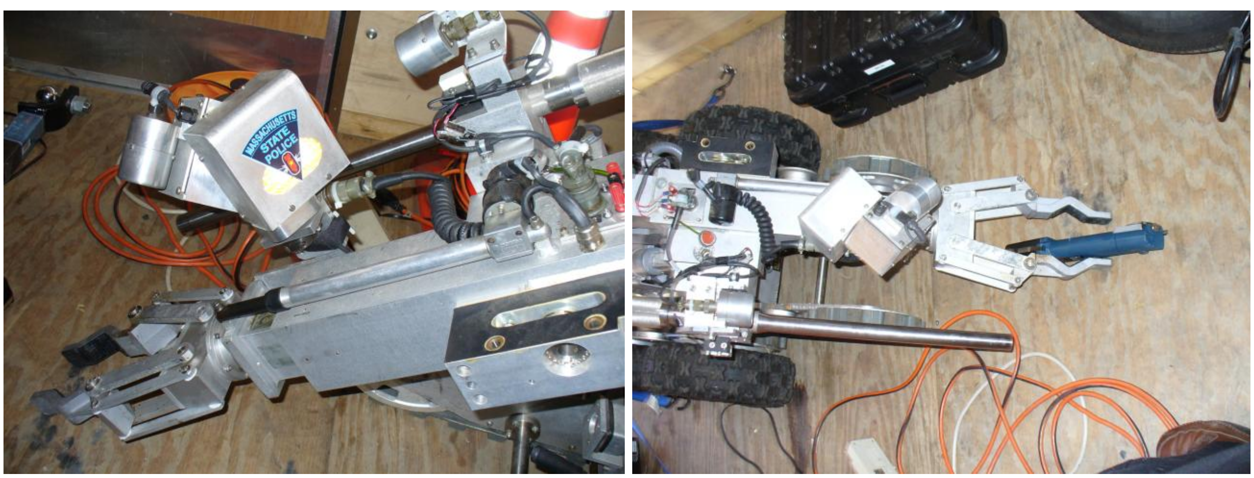


Figure 4: Trial Cordless Cutters Mounted On MA State Police ANDROS Unit

TPI has historically worked closely with Qinetiq (Foster-Miller), maker of the TALON robot (Figure 5). TPI has had access to their support staff and learned about the present experiences around the world with suicide vests and IEDs chained to personnel or facilities. TPI has also looked at future integration with the TALON arm, and the interfaces required.

Figure 5: Trial Cordless Cutter Mounted On TALON Checking For Camera Angles And Control

Beyond the need to be compatible with the ANDROS series, no specific requirements were set. TPI used its experience and discussions with operators and robot manufacturers to start to construct notional requirements. These requirements continued to evolve with time and additional operational experience, but they provided a start point for the design cycle. The following discusses the requirements and design implications associated with each choice.

At a top level these initial requirements included:

- Provide an add-on tool that can remotely cut through mixed materials such as fabric, cable, buckles, zippers, chain
- Single tool rather than a double bladed system
- Minimal control
- Not harm the human (hostage)
- Adaptable to legacy robots
  - Minimal on-arm weight
  - Self contained power source
  - Minimal interface with electronics
  - Minimal interface with comms/control
- Low cost
- Low visual profile

At a design level these overarching requirements took on meaning as follows:

2.2.1.1 Single Tool For Different Materials

It was assumed that the cutter would need to cut through a range of materials including cloth, rope, cables, and possibly chains. In most cases the material would be a mixed construction and often integral to one another such as buckles and cloth, or zippers and cabling. While no specifications exist for what materials or how thick they would be, we used tactical vests made of Kevlar and foam and fastened them with cable, locks and chains. We made no attempt to avoid zippers, buckles, Velcro or buttons.

The mix of materials seriously complicates and compromises optimum cutter selection as used for single materials. So called rug cutters can cut through 48 layers of Kevlar with ease, but stall flat on a button. Saws jam quickly with cloth. While there are cutter designs that are optimized for a given material, they operate under a very narrow band of blade type, rotational speed and torque.

Initially it was assumed that two blades would be used, where we would activate one blade for a given material and then the other where appropriate (the double in the original name Double Dervish). It was discovered that the integrated nature of the target materials, the 3-D nature of the problem and the poor visibility and control relative to the cutting point would not realistically allow the application of two cutters. Two cutters would require good feedback, to support complex positioning to get the cutters to work within the same kerfs, which would increase cost at less reliability. Blades designed for specific materials are optimized with a limited range torque and rotational speed doubling the need for transmissions, electronic closed feedback circuitry, on off and hand off, etc.

In order to increase simplicity and reliability, TPI decided to focus on a single cutter design. A single cutter simplifies the mechanisms, and control improving reliability and lowering cost. There was some sacrifice to cutting speed relative to a matched material/ cutter, but the loss of speed was minor compared to the other penalties.

While by contract we only needed to cut vests off, discussion with users indicated that hostages were often tied or chained to a wall, or the IED could be within a backpack that was fastened to a structure such a pipes or fencing. The cutter was therefore designed around the worst case materials assumed to be 3/8-in aircraft steel cable or chain, or lock hasps. The success of cutting cables and lock clasps also broadened the general applicability of the tool to other mission components including cutting sheet metal and the potential for door locks in a breaching application.

2.2.1.2 Control/ Arcing

All robotic arms operate through a series of pivot points which makes linear motion difficult. Most ANDROS systems include a wrist and linear actuator to provide close-in control. The TALON and the PACBOT systems lack the linear actuator which means that in-out motion can only be achieved by the arm movement which creates an arcing motion, or through movement of the vehicle itself. Testing has shown that the control was rough, and would work but only when the vehicle was initially positioned in an optimal orientation.

The result was that the catch and feed mechanism needed to be simple and forgiving of textile characteristics to keep the material feeding into the cutter. A shoe was designed not only to protect the substrate, but also provide continuous contact with the target.

The cameras for visual feedback are located on the robot and are usually in line and behind the gripper resulting in poor vision. The design was constructed to minimize its visual profile to maximize observation.

2.2.1.3 Speed and Feed Rate

The mission clearly needs to be finished as soon as possible, however actions need to be deliberate, especially with HBIED. Cutting rates were not considered to be a critical parameter, and no effort was spent on maximizing cutting speed. Since feed control was difficult, the Dervish was designed to sense stall conditions prior to jamming and to reverse itself. Beyond simply preventing jamming, it allowed for maximum feed rates for a given stall threshold. While the Dervish was designed with a single universal blade, if the target material was known prior to be sent down range, an optimum cutter blade could be used and the stall thresholds changed (at the point of deployment).

2.2.1.4 Gripper Positioning

There was no real consensus of where the cutter should be mounted. The goal was to minimize interference with the gripper and disrupter functions to make it a one-trip mission. The placement of the cutter on the outside of the gripper conserves the gripper motion, especially with parallel type grips. Putting the cutter on the inside (Figure 6) was best for sight lines, but meant the gripper function was compromised. The ANDROS has a very convenient Picatinny rail on the outside of the gripper fingers, but it would cause the cutter to clearly block the disrupter shot line. Placing the cutter on the outside of pincher grips (Figure 7) resulted in lateral arcing and tougher control. Some of the vehicles are set up with cameras laterally offset so that sight lines were blocked when positioned on the outside.

Figure 6: Cutter Positioned On The Inside Of ANDROS Gripper (View From OCU)

The placement of the cutter on the gripper has direct implications on the on/off switch design. An inside position would allow a momentary or bump switch to be operated by closing the gripper. A bump switch operated off the ground can also work, but because of the angle of attack, requires a extender so that it can reach the ground. The extender in turn can block the view of the bow camera. The use of spare control ports commonly found on the Remotec systems were the ideal solution, but may not be available on the smaller robot systems.

Figure 7: Cutter Positioned On The Outside Of A Pincher Gripper Of The TALON

A single solution to the positioning would not be likely found due to the customizing of all the different variants. The Phase 2 effort would focus on the most flexible design which was a drop-off design that would allow the operator to drop and pick up the cutter while down range.

2.2.1.5 Jams

Effective cutting of either cloth or metal must strike a balance between feed rate and feed force to prevent jamming. Jamming not only is non-productive, the stall currents can drain a battery almost instantly thereby terminating a mission, and worse can over heat the control circuitry to the point of burning up the system. Manually controlled cutters or grinders are not as susceptible to burn out because of the excellent human touch, visual and audio feedback by that results in backing off or temporarily turning off the system in case of a jam. The robotic application however does not provide that level of feedback. While most robots have an audio receiver most are pretty poor quality and economical tactile feedback systems are still somewhat in the future. The cutter system therefore needs to be self controlled.

The TPI cutter automatically operates within a band of cutting resistance as measured by a balance of current and voltage draw. Providing a real time feedback of this current and voltage draw would require TPI to integrate the system into the robot control system, however most of the robot developers are reluctant to divulge the inner workings of their control logic.

JAUS, which was a common control language interface among recent military systems, was considered by many robot developers to be cumbersome, requires special hardware, and software and does not exist on systems built prior to 2004. By using a self contained microprocessor, the control feedback would be compatible with all communication architectures. JAUS compliance has not yet made an impact on fielded systems, and while the system would be easily JAUS compliant, it was not felt to be a priority in the near future, yet the Dervish would be upgradeable at any time in the future.

As will be described later in this report, threshold balancing offers a number of other power saving advantages as well, but the principle one was to stop the operation before a stall condition prevails. In addition to the self monitoring and control, a feedback system was deemed necessary to help the operator understand the status and difficulty of cutting. Since the TPI cutter did not tap into the control logic and communications path, the status information was provided by was a series of light mounted on the cutter electronics (Figure 8) that can be monitored by the robot cameras.

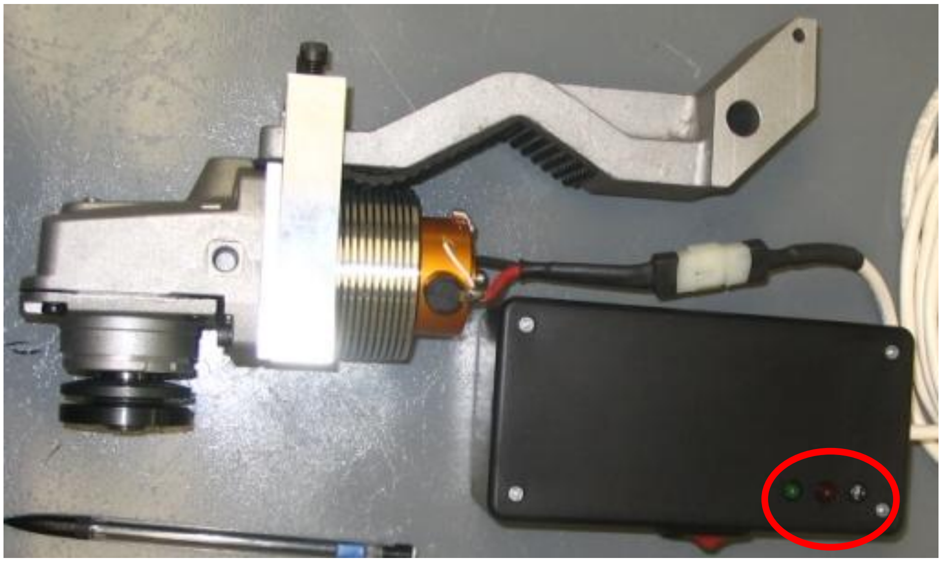


Figure 8: Cutter Status Is Provided By LEDs Visible Through The Normal Robot Camera View.

2.2.1.6 Arm Strength

The arm strength and tipping force limits of the smaller class robots is limiting. The arms must not only support the cutter but apply and be able to resist the cutting thrust and applying feed force, especially at full extension. The PACBOT and TALON can only reliably carry 7 lbs at the end of the arm, including the mounts and on older units less than that. The ANDROS has more than sufficient strength to hold any cutter. The heavier the tip load on the arm, the more difficult it is to control the position. A tip weight of no more than 5-lbs seems reasonable but is difficult to accomplish if the batteries are part of the cutting head. The limited tip weight also restricted the addition of other features such as linear actuators, rolling shields, among others.

A key tradeoff was to decide where to place the electronics and the battery. It was always good to keep the power and electronics together to minimize cabling, keep the parts count down and ease set up. But while the electronics do not weigh much, the battery weight can be significant and the volume would make mounting difficult. The round arms of the TALON and PACBOT further complicate mounting. Splitting off the power pack and mounting it on the robot deck makes the tradeoff to more power and longer duration simple. The down side is that if the plan was to be able to drop the cutter while performing other operations, then the cable would be in the way and would make maneuvering and subsequent pick-up difficult.

2.2.1.7 Batteries

Since the power for the cutter would be self supplied, TPI has the luxury of experimenting with optimum voltages and battery chemistries. The trade off was a function of cost, longevity, and weight as well as recharging complexity. By remaining independent of the vehicle power, which can range from 5V to 36 V, TPI can select the optimum system without the need for power conditioning.

2.2.1.8 Not Cutting The Undersurface

In hostage and suicide cases it may not be acceptable to cut the person during removal of the vest. This can occur through abrasion, cutting into the skin or by heat build-up. A UHMW guide-shoe acts as a stop and prevents deep abrasions or cuts (Figure 9). The shield would be manually removable at the start of the mission if the cutter wheel was to be used to cut through door locks or hinges. Removal of the shield would provide better depth penetration and the ability to cut though single sided surfaces (such as door panels).

Figure 9: Guide Shoe To Prevent Harming The Hostage.

2.2.1.9 View angle

Low profile would be preserved where possible to minimize interference with the view angle. Most vehicles have an arm mounted camera whose view may be blocked by the body of the cutter. Adding the batteries on board would further add bulk to the system. The positioning and placement of the cameras and cutter have the greatest amount of flexibility on the ANDROS. Center line and tangent cut reference marks make orientation much simpler. Not all models have the same camera set-up and we found great solutions for one set up that were completely unworkable for others. The emphasis was to minimize the tool profile to minimize obstructing the view rather than rely on a single position that might not be applicable to other models.

2.2.1.10 Cost

The cutter was essentially an accessory and as such its cost need to be reasonable within the context of the robot and the budgets of the law enforcement community. Additional sophistication can be added but at extra cost whereas adaptations of off the shelf tools would be cheap but have performance drawbacks. As a starting point TPI has established a maximum cost of $6,000 and used this as a design threshold.

2.2.2 Design & Fabrication

We had several design philosophies going-in that shaped the progress of the program. The principle one was to minimize unit cost, and we hoped to do so by modifying commercial off the shelf systems (COTS). We tested COTS units, looked at the components and tried to focus on keeping as many parts as possible. Such an approach would not only leverage already proven designs, it should minimize the logistics tail in terms of maintenance and repair. Unfortunately, as would be seen this was not really achievable in the end.

COTS systems are designed for manual use and mass markets. Low cost came at the price of low efficiency or low performance components. Parts were quickly being outmoded, many are considered proprietary and therefore could not be incorporated into our design, and overall the performance in an automated mode did not meet expectations.

This realization did not occur until well into the testing and design. The system as it stood at the end of Phase 1 was largely a standalone design, but a second generation system (the Phase II product) would be able to improve operation considerably if unencumbered by trying to incorporate COTS components. In the end the cost may be slightly higher, but without performance compromise.

2.2.2.1 COTS Characterization

Existing robots have limited feedback capability as constrained by sensor limitations, RF bandwidth, available channels, power, and computing power. Audio and even visual feedback can be very limited and without depth perception. Motor lugging, stalling, arcing, blade dulling or clogging to name a few, are difficult to ascertain from a visual feedback only, especially if it was to be used as an anticipatory action rather than a reactionary tool. Human hands-on control is very perceptive and uses force feedback, vibration, torque, sound, visual and even smell to adjust the amount of pressure applied. It was incumbent in the design process to minimize the need for external control. It was assumed that the best control would be visual based only, and the perspective may not reflect the actions needed for cutters. A system that contains the means to be inherently self regulating would be best and it was the goal of this effort to provide that capability. The goal was for the controls to be limited to wheel selection, feed rates and on/off.

TPI designed a test stand to characterize various cutters and quantify the force needed to cut a range of materials. The test stand also allowed us to get quantitative measurements for assessing differences and improvements in efficiency. A passive and independent force feedback control loop was designed that balances the cutter wheel rotational speed as a function of current draw (which in turn was related to the resistance of the material and the feed rate) to prevent jamming. While no numbers exist for what materials or how thick they would be, we used tactical vests made of Kevlar and foam and fastened them with cable, locks and chains. We made no attempt to avoid zippers, buckles, Velcro or buttons.

A survey of various commercial off the shelf (COTS) cutters and grinders was initiated. We focused on COTS cordless systems (Figure 10). After review, 3 systems were selected for more intensive testing and characterization including:

- Eastman Workerbee
- Emery
- Dewalt

Figure 10: Tested Cutters - AC Powered Textile Cutter, Battery Operated Grinder, Battery Operated Snips, Battery Operated Textile Cutter. Not Shown Are The Bosch/Emery Units.

The Eastman and Emery are cloth or rug cutters, while the Dewalt was designed for grinding. The general specifications of each are listed below:

- DeWalt DC410 18V 4-1/2" Heavy-Duty Cordless Grinder / Cut-Off Tool
    - 6,500 RPM provides high power for cutting and grinding applications
    - Spindle lock allows users to change their wheels quick and easy
    - Metal gear case dissipates heat for longer bearing, gear and motor life
    - Voltage: 18V
    - No Load Speed: 6,500 RPM
    - Spindle Lock: Yes
    - Spindle Thread: 5/8" - 11
    - Use Wheels RPM Above: 10,000 RPM
    - Tool Weight: 7 lbs.
- Eastman WorkerBee WB1 Precision
    - 7.2V Battery Cordless
    - 2 1/32" Rotary Knife Fabric Shear CUTTER
    - Adjustable BladeGuard
    - 2000RPM
    - 60Lb Torque
    - Manual adjustable 2-Pos. Handle
    - Push button blade sharpener

- Emery Portable Electric rotary Shear
  - Cuts up to 10 layers, of textile, ½ carpet, carpeting, PVC, linoleum, foam, rubber, leather, cork
  - 60mm 10 sided rotary blade and stationary carbide blade are self sharpening.
  - 9.6VDC NiCAD, recharges in less than 1 hr
  - Single charge cuts 800 ft of cloth, or 300 ft of carpet
  - Weight: 1.5 lbs w/o battery, battery 1.1 lbs, total 2.6 lbs
  - Length 9.5" with battery 12.5", width 2.25". tall 3", girth 6.5"

A specialized test fixture was constructed based on a computer controlled data acquisition system that can mount cutters or motors with cutter on an X-Y translational table. Figure 11 illustrates an overview of the entire system. A target material was mounted on the bar, and parameters are set (speed, thrust, stroke, etc.). Figure 12 shows the cutter attacking a 3/8 cable. Figure 13 illustrates the sample materials tested from cloth to cable, chain, chain link fence and strapping. In addition several different styles of tactical vests were procured and cut. These vests are variously constructed of Kevlar or ballistic nylon, and are a better representation of pockets, zippers, etc. Testing was then a hands-off operation, and the voltage and power were recorded in Excel and plotted. The raw data files are relatively large and are not included in this report.

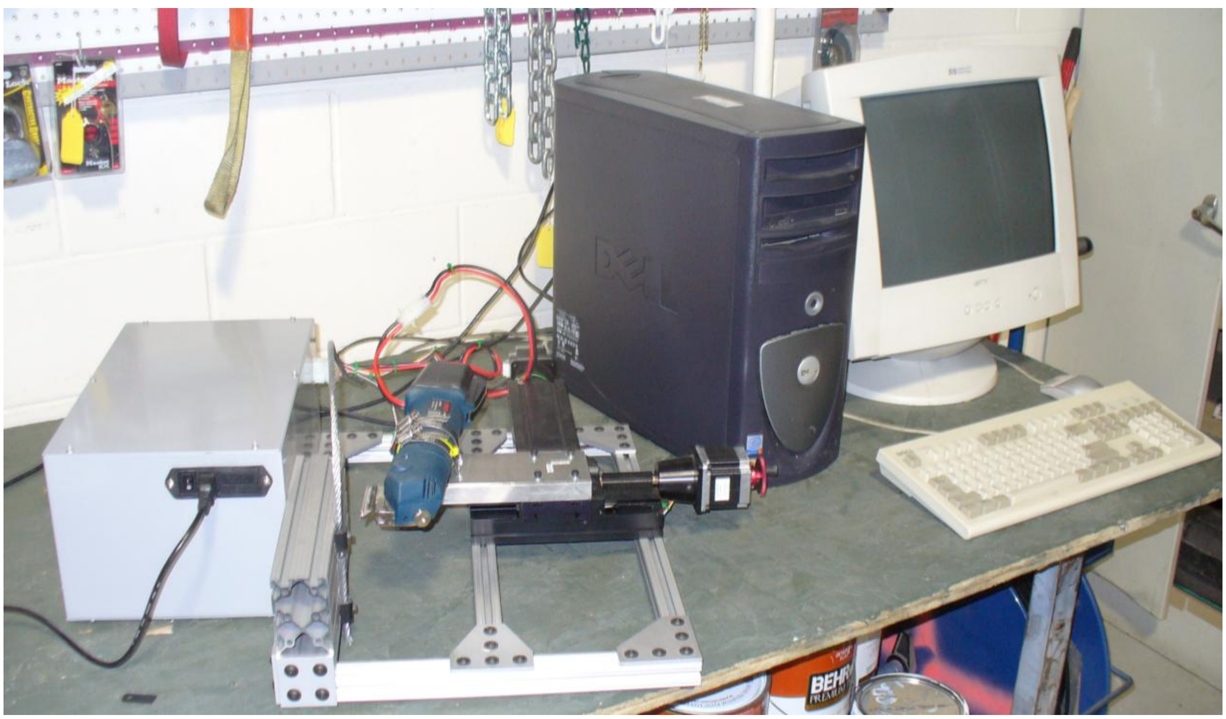


Figure 11: Overview Of Cutter Characterization Test Stand

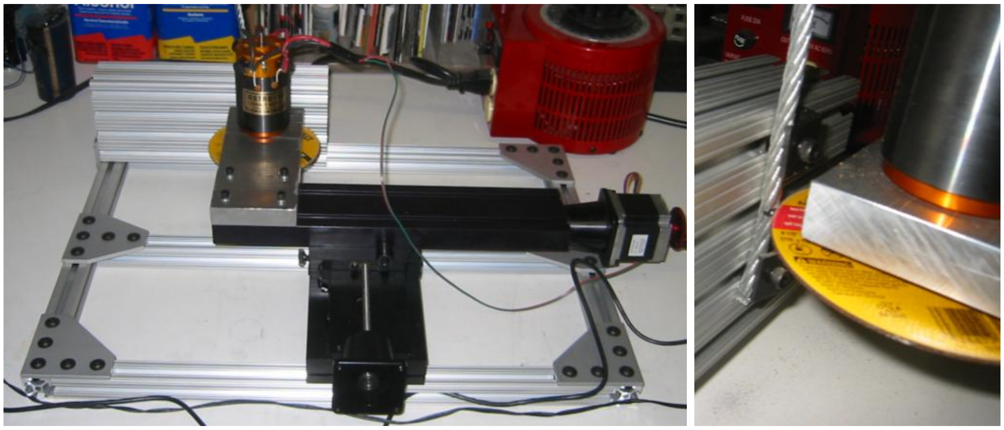


Figure 12: Microprocessor Controlled X-Y Table For Characterizing Cutters And Motors. Cutter Attacking A 3/8-In Cable.

Figure 13: Testing Materials For Cutting Including, Wire, Straps, Cable, Chain, Bungee Cords, Zippers, Cloth.

2.2.2.2 Cutter Selection

The textile cutter designs are very well suited for cloth and cut through them with ease. The issue is that they jam and dull if the cutter encounters a zipper, or steel webbing, or wire. The cutters work on shearing much like scissors, and the octagonal and 10-sided cutters which have flats cut into the perimeter, act as a scissor shearing action. Snips are slow and require positioning with good depth perception. Control was difficult and small cuts consume considerable energy. Where a linear cut was required such as on a suicide vest, the number of cuts required was large and not a reasonable solution. Draw knives can cut through material as well, as long as the composition does not change. Reciprocating cutters are also material limited. Rotary cutters were clearly the preferred system. Most rotary cutters are specialized for the material that they attack. Blade angles, cutting speeds, shape, and thrust are matched and optimized for the material. If we were to only cut fabric; rug cutters would be a great choice but they completely fail when cutting zippers, buckles or cables. Forcing the cutters to operate outside of their optimum operating range slows down the cutting process and consumes enormous amounts of power. A jam spikes the voltage and current draw and can burn out the battery and potentially the circuitry. At best the mission would fail prematurely; at worst the system would be irreversibly damaged and it can actually heat the circuit to the point of melt down.

Whereas the initial premise was that two wheels of different properties (steel cutter and cloth cutter) would be required, we found that commercial grinding wheels cover a board range of materials thereby greatly simplifying the operation. Rug cutters can't cut steel and steel cutters tend to gum up and can't cut cloth. A grinding wheel can cut both. To be sure a specialized cutter with its dedicated blade and blade speed and torque was far superior, but the unknowns of the downrange situation, and the cost in time for shuttling the robot back and forth lent a lot of weight to an option utilizing a grinding wheel.

Since the objective was to cut through such a wide range of materials, we quickly found that so called 'cutoff' grinders were the best choice. DeWalt DC 410 Cordless makes a grinder that has a very good versatility and we tested the system using the instrumentation described previously. The DeWalt grinder (Figure 14) was a self contained system that could be strapped onto a robot and could be made to work however we found on closer examination it had significant drawbacks. The weight would rule out its use on the TALON and PACBOT and its bulk and form factor made it hard to mount, hard to control and it tended to block the camera sight lines. Tool weight was 7.2 lbs. which was too heavy and bulky for use on smaller robots, and jamming during testing burnt up circuitry and batteries. In a simple fixed test often seen in demos, the DC410 would operate well, but under realistic mission conditions the batteries would quickly die and probably cause permanent damage to the system.

Figure 14: Cordless Rug Cutter, TALON Gripper, And Dewalt DC 410 Cordless Grinder Without Batteries

2.2.2.3 Motor Design

The cutting speed of the grinder wheel was 13,300 rpm; however the idle was 6,500 rpm. This results in a battery life of only 15 minutes at no-load (idle). This was a result of both the low efficiency motors and limited battery capacity. The DC410 uses 45-50% efficient motors that consume fully 80% of power while simply idling.

Operationally this means that the system could run out of battery power while just positioning the cutter. Even with a down range on-off switch there was a great deal of time in positioning and the inefficiency was not considered to be acceptable.

Clearly a down range on/off switch would help, but it requires a modification to the system, and while modifications are taking place the overall efficiency of the system could be vastly improved.

The solution was to replace DC4510 motor with more efficient system (85% vs. 45%). A mid level motor system was selected that was still inexpensive and had the same form factor as the DeWalt that allowed us to keep the right angle transmission. The Astro-90 motor added $150 to the system, however motor efficiency essentially doubled. Figure 15 illustrates the new motor system. Further improvements can be made in the future with higher end motors, or the use of brushless motors; however the incremental improvement in performance would not be nearly as dramatic. Coupled with the control electronics discussed next, the new motor design resulted in a significant performance improvement.

Figure 15: 85% Efficiency A-90 Motor (Bottom) In The Same Form Factor As The DC410 Motor (Top).

2.2.2.4 Electronics Design

When a DC motor turns, the coils passing by the armature magnets creates a back electromagnetic force (emf) potential or voltage. That voltage can be correlated to rotational speed. Since the motors have discrete magnets the back emf was not smooth but very spiky, but by averaging the voltage the motor speed can be determined. The intent was to use this emf to 'sense' the motor speed as an input to the control circuitry. The nice feature about using the back emf was that no onboard sensors are required, and the wiring at the business end of the motor was simple and unchanged. By comparing the motor driving current with the back emf we can determine what the rotational resistance was for a given motor and we can use that to control how it behaves.

The idea was to set thresholds that bound the motor into certain performance envelopes. The lower threshold was the idle condition, and the upper threshold was the stall condition. In the idle condition, the cutter motor turns at very low speed. When the blade encounters material and the cutting resistance goes up, the motor controller increases the current and therefore the motor speed to the level needed for effective cutting.

If the material was force fed into the cutter and the resistance spikes up, the wheel stops, the back emf drops yet the feed current rises. Under normal conditions this would drain the battery and potentially damage the motor, but by monitoring the unique condition of high current and low back emf (voltage), the motor can be stopped or reversed to avoid the jam and prevent damage to the system. The block diagram for this control approach was shown in Figure 16.

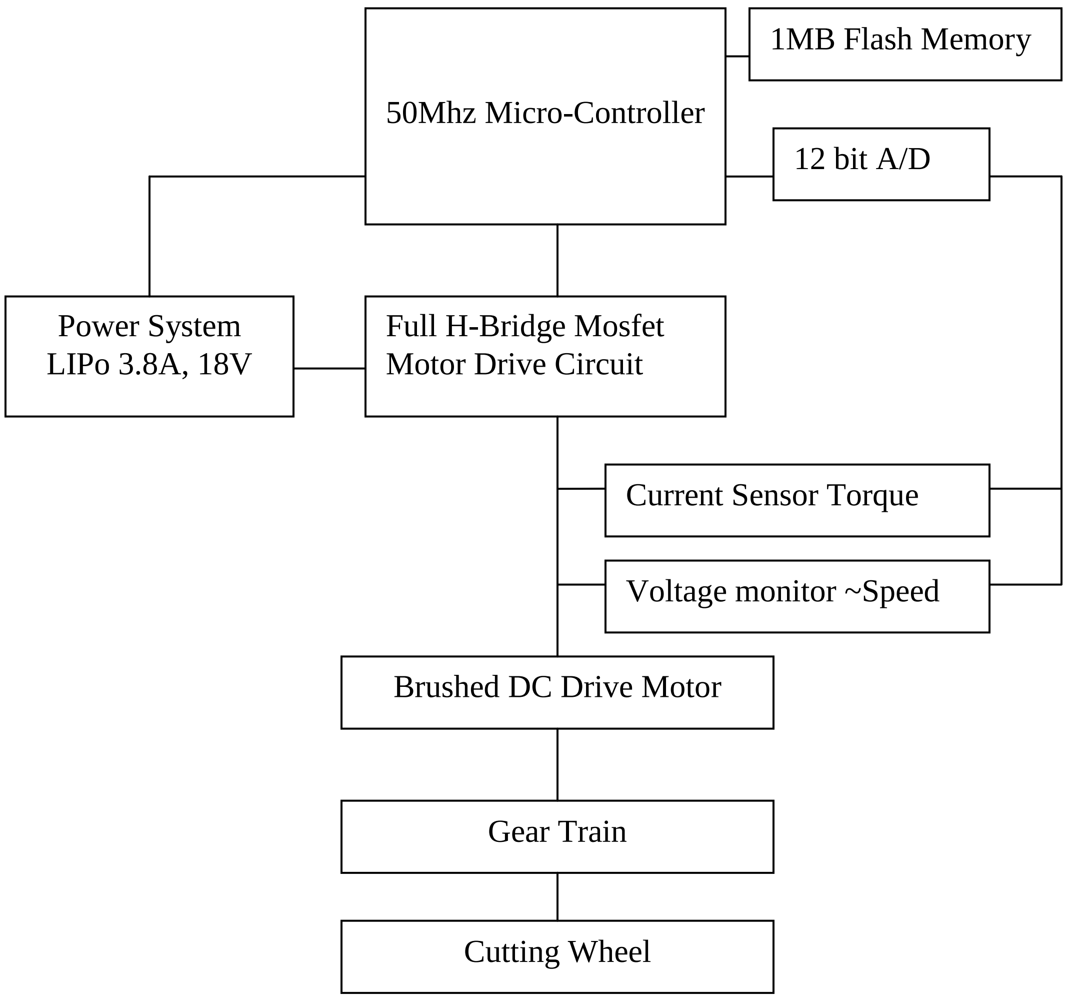


Figure 16: Block Diagram Of The Cutter Closed Loop Feedback Circuitry

The principle advantage of the back emf approach was that it was simple, rugged and inexpensive. The disadvantage was that as the motor heats up the efficiency of creating back emf changes and therefore the thresholds are changing. Also a considerable amount of heat was generated that must be accounted for at both the motor and the control board side.

By adding the feedback control, idle current draws dropped from 80% to 10% resulting in savings for the motor, power consumption and the electronics themselves. The system acts much like a software driven fuse. Once a power threshold was reached, the system assumes a jam condition was approaching and slows down or reverses. Simultaneously a red led was lit on the electronics box that would alert the operator a jam was occurring so that they can back off. Since vehicle and arm control was on the loose side, the addition of the self adjusting feedback provides the operator with significantly greater control bandwidth and allows them to effectively cut a wider range of materials.

In order to set the thresholds on the controller the motor had to be characterized. The motors are not equipped with Hall effect sensors, so rotational speed was monitored using the back EMF or voltage draw. Testing was performed on the test rig which fixed the speed and penetration rates and the data were recorded digitized and recorded on computer files. We could then test and adjust the thresholds to see effects of changing the parameters. Figure 17 illustrates the test set up and Figure 18 shows some of the data.

Figure 17: Test Rig Used For Characterizing The Motors And Setting Stop Thresholds

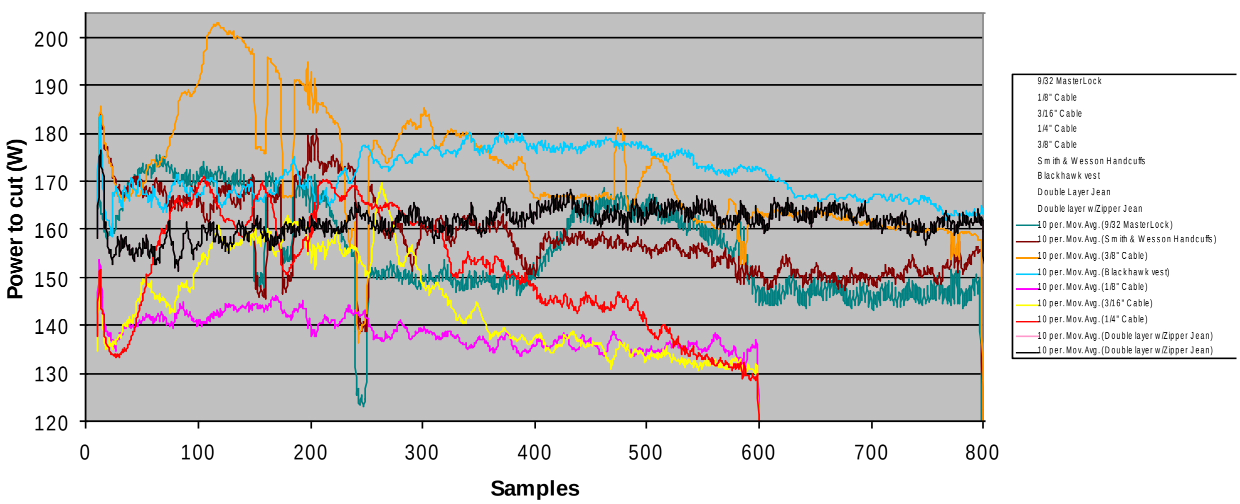


Figure 18: Sample Data From Cutting Test To Characterize The Motor.

Resistance thresholds for stopping were set at fairly conservative levels to insure survival of the prototype electronics. The system was bolted on the test rig and performance monitored mostly for control and jam tendencies. Speed of cut was very robot and situation dependent and cut rates were not recorded as they would be essentially meaningless. Objects that were cut include (Figure 19 through 23):

- 9/32" Master lock
- 1/16", 1/8", 3/16", 1/4, 3/8", 5/16" steel Air craft cable
- Hand cuff
- Plastic coated A/C Cable
- Kevlar
- Ballistic nylon
- Black hawk vest, 10 layers + Velcro+ YKK zipper + foam
- Double blue jean @ hem
- 4-layers blue jeans + brass zipper
- 3/8-in chain

Figure 19: Jeans And Brass Zipper Cut By The TPI Cutter

Figure 20: Cabling Cut By The TPI Cutter

Figure 21: Ballistic Nylon Cut By The TPI Cutter

Figure 22: Multi-Layers And YKK Zippers Of A Tactical Vests Cut By The TPI Cutter

Figure 23: Lock Shanks Cut By The TPI Cutter

2.2.2.5 Batteries

Initially TPI tried to use Dewalt batteries since they are common available and used by many bomb squads to power other tools. The idea was to use as much COTS componentry as possible to take advantage of the mass production availability and low cost. A closed loop feedback system was designed and built that would be inserted in between the battery and the motor Figure 24 shows the boards. By doing so we could gain autonomous control of any Dewalt grinder, and if we used a Dewalt with the upgraded motor, the overall efficiency would improve by a factor of 3-5 times.

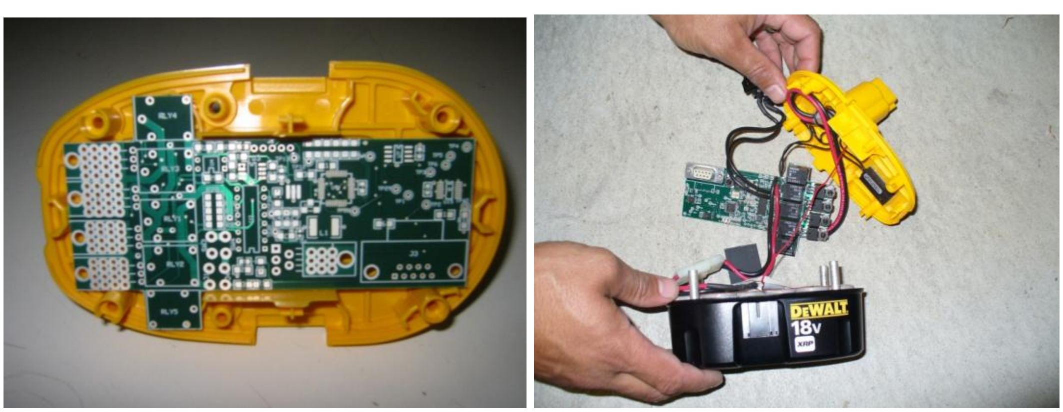


Figure 24: Closed Loop Control Circuitry Inserted Into COTS DC410 Battery Housing

A circuit board was designed and fashioned to fit in between the battery and the insert section of the battery to the tool. Note the cruciform layout to fit seamlessly within the battery compartment. Integration was pretty straightforward though it would necessarily occur at the factory. The circuit only added roughly a ¼ -in to the length of the battery housing (Figure 25).

Figure 25: Circuit Board Only Added About ¾-In In Thickness To The DC410 (Left) Compared To Unmodified System (Right)

Tests showed that functionally it worked well.

The problem was that the DeWalt grinder has such a poor form factor for mounting on any robot that keeping the battery on the grinder was not reasonable. The batteries were bulky and heavy and of a form factor that made attachment to the arm cumbersome. The handle which was located between the motor and the battery was wasted space only containing the switch, which unnecessarily increased the overall length by 4 inches. The added battery weight on the end of the arm was too much, especially for the smaller TALON and PACBOT vehicles.

To accomplish this as noted above, we separated the housing and designed a circuit board to fit within the housing, however this approach had several disadvantages:

- Firstly there can be some liability issues with modifying the battery system that the supplier may not be happy about. The batteries are actually constructed of a series of battery cells that must be charged in a certain order. The charging circuitry was included in the housing and the TPI electronics had to incorporate it in our design.
- Secondly the battery, which in this case was the 18V NiMH system, was bulky and cumbersome to mount. The Remotec arms are more robust but the TALON and PACBOT arms are sleek and slender with the limitation that they are not very compatible to adding on accessories. This forced the decision to mount the batteries and the electronics on the deck.
- Finally we were so successful keeping the look and feel of the supplied batteries the same, that confusion easily crept in as to which was an unmodified COTS battery as opposed to one with the circuitry built in. Down the road, it was assumed to be highly likely that without a built in key to prevent use, the operators would eventually revert to using conventional batteries without any of the protection and benefits associated with the TPI designed electronics.

The alternate approach was to separate the batteries from the motor via a tether. This allowed the heavy batteries to be mounted on the robot deck where it was convenient, and to keep the weight off of the arm. Visual profiles at the griper were slimmer, it was easier to mount, and the battery box design could be flexible with more room for cooling the electronics and greater battery capacity.

With the decision to go off board, the need to miniaturize goes away. The electronics board was redesigned with greater space to prevent heat buildup and heat related damage to the traces and components. This action would improve manufacturability, cost and reliability.
Once the decision was made to separate out the electronic and batteries from the motor, we started to examine the advantages of lithium polymer secondary (rechargeable) batteries.

We experimented with replacing the 18V NiMH batteries with lithium re-chargeable which would either allow a near doubling of capacity or a reduction of weight by half for the same capacity. The charging circuitry proved to be tricky. While we wanted to tap into the existing circuitry that DeWalt provides it was well protected with proprietary shields.

NiMH /NiCad batteries provide 1.9 amp-hours at 18 volts, and weigh 842 grams and are 3,740 cubic centimeters without the housing. Lithium systems produced 3.8 amp-hours or double the capacity at only 400 grams (half the weight). The appeal to use the smaller lighter lithium's can be seen in Figure 26 where they are compared to the NiMH of the same capacity.

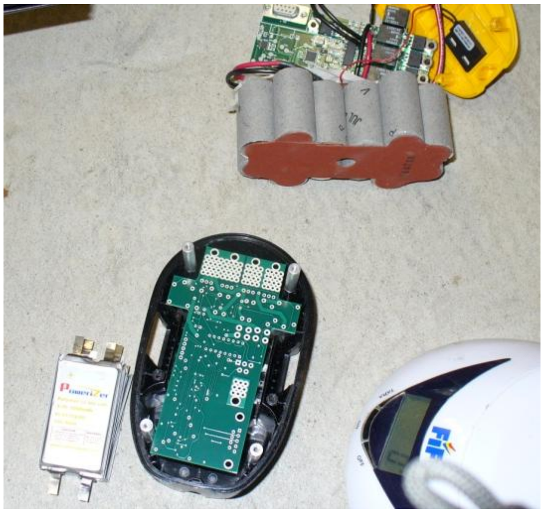


Figure 26: Lithium's (Silver And White Box) Vs. Nimh Batteries (Cylinder Bundle) Of The Same Capacity

There are some considerable down sides to Li batteries however. The resulting danger of over-charging lithium's is well documented and we decided after considerable experimentation with the deWalt charging circuitry to stay with NiMH. They are safer, cheaper (x4), and with the batteries on deck, weight and volume was less of an issue. If we need to we can revisit the lithium battery solution at a later date. The discharge profiles of the NiMH battery packs still need to be established so that their affect on the threshold limits as the battery loses charge over the operational cycle was understood and can be compensated for.

Placing the batteries on deck also allows hot swapping batteries, adding batteries for even greater power, etc. Actual placement needs to be worked out with the operators and would be platform and other mission configuration specific. Initial testing on the Remotec, TALON and a cursory look at the PACBOT indicate that there was plenty of space for the battery/electronics box.

2.2.2.6 Drive

Once the electronics and battery were separated out and the DeWalt motor and housing was eliminated the only thing left was the right angle drive. The end result was a highly compact system. The right angle drive was retained because it had a good design for the output shaft and cutter wheel and was already grooved for the safety shield or cowling. While a lighter drive could be manufactured the advantages were not significant enough to warrant the cost and effort. Figure 27 illustrates the combination of the A90 motor with the right angle drive. Figure 28 illustrates the complete system with the control circuitry and batteries included in the plastic housing.

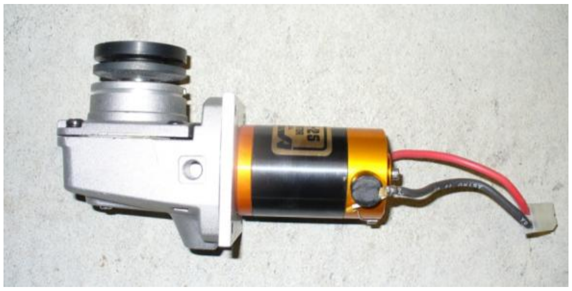


Figure 27: A90 Motor Adapted To The DC410 Right Angle Drive With Heat Shield Removed

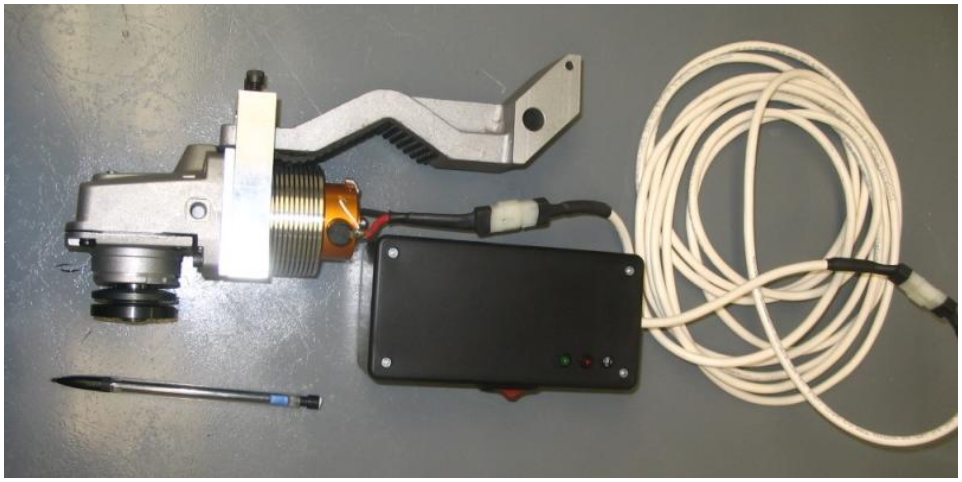


Figure 28: Complete System In The Control Circuitry And Lithium Batteries Included In The Plastic Housing With 6-Ft Power Cord Tether Mounted To Remotec Gripper Finger.

Figure 29 illustrates the system as tested on the TALON. The power and electronics can be in a separate enclosure connected by a simple cable located up to 6 feet away without serious power loss. This allows the power to be mounted on the deck of the vehicle in a place of convenience.

The cables need to be zip-tied to the arm, but this significantly reduces the arms cantilever weight and improves the sight lines.

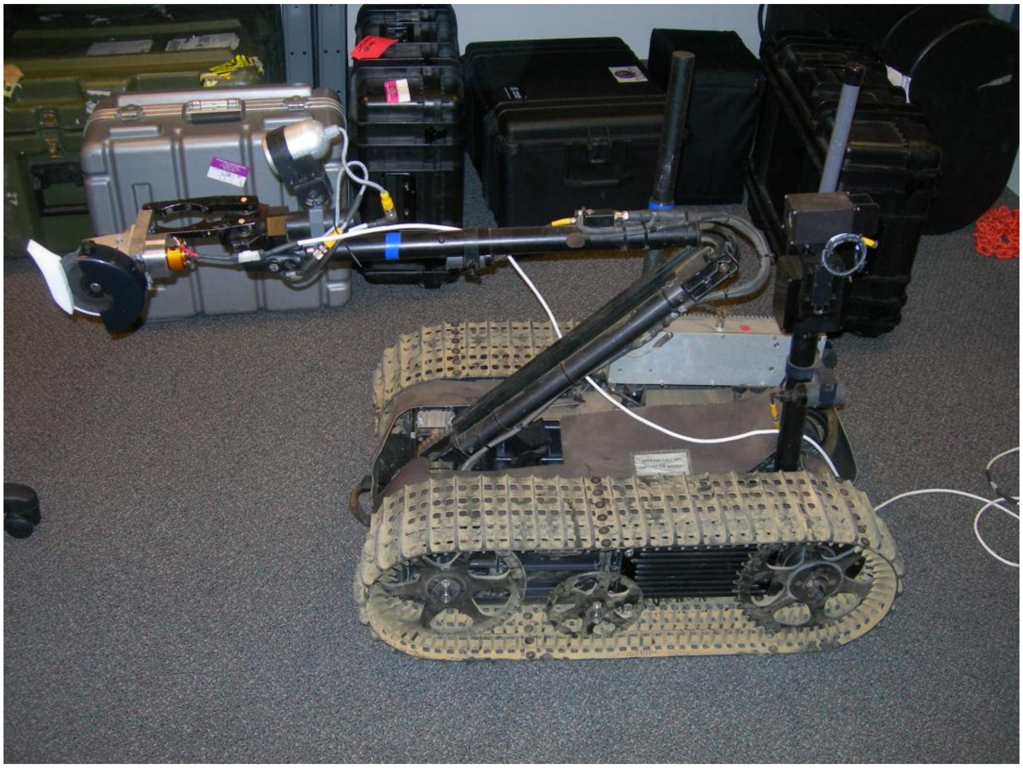


Figure 29: Dervish With Separate Power Head And Battery/Controls Package Mounted On TALON

2.2.2.7 Guard

There was a need for two guards – a top half which would protect the EOD tech while mounting a bottom shoe guard to protect the victim for the blade cutting too deep (Figure 30).

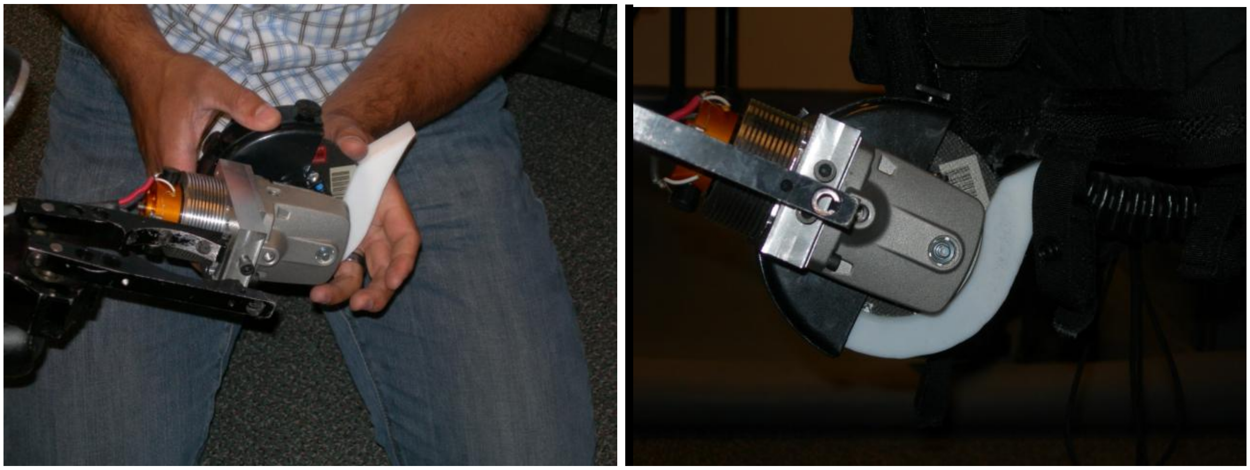


Figure 30: Upper And Lower Guards Mounted On A TALON Pinch Gripper.

By keeping the DC410 right angle drive we can also use the same top cowl system found on the COTS units. The cowl prevents the upper half of the blade from making inadvertent contact with any EOD personnel during mounting and handling. Since the system can be hand operated as well as robot-mounted, a top half guard was a simple yet logical feature. The top guard was clamped on the transmission with an over center latch and can be rotated into any position. Once fixed and sent down range though, the cowl position remains fixed.

The lower guard shoe slips under the material to be cut and captures the material between itself and the cutting wheel. Not only does the lower guard protect the victim, it holds the material in place. This was particularly useful with loose material such as chain which otherwise bounces around and was difficult to cut.

The bottom shoe was constructed of Teflon, and was screwed in place to the transmission housing. The guard was manually positioned prior to going down range. Beyond the limited wrist and arm movement any readjustments for the cutting point would require a return to the command post, manual re-adjustment and then return to the target site.

2.2.2 8 Positioning

The Remotec grippers have a large surface area to work with and mounting offers considerable flexibility. The newer gripper fingers also have a Picatinny rail mounted on the outside which makes mounting simple.

The Cutter was positioned on the outside of the gripper thereby permitting continued use of the gripper. The attachment piece was near the end of the gripper which resulted in a big cantilever load on the arm. Moving it closer to the base of the gripper though would result in the inability to close the gripper unless a special attachment piece was made for each vehicle design. Using the base of the gripper in the open position would put the cutter at an oblique angle and make operation difficult. Figure 31 shows the TPI cutter mounted on the inside of a Remotec gripper finger showing both guards and the bump switch. The Figure also shows the same arrangement mounted on a Remotec robot with the electronics mounted on deck.

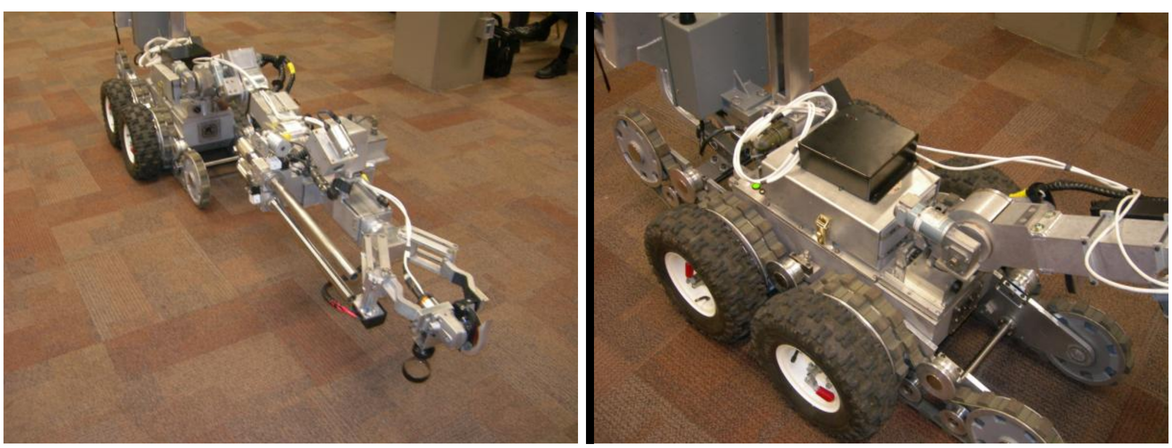


Figure 31: Dervish Mounted On The Inside Of The ANDROS Gripper And Box Double Stick Taped To ANDROS Deck.

2.2.2.9 On/Off Switch

There are several means of turning the system on and off. Most of the robots have auxiliary outputs for accessories or firing circuits. Figure 32 shows the location of the auxiliary outputs for the MA State Police ANDROS. These are already wired into the communications and control system and can be operated from the OCU. The voltages are not enough to drive the cutters so the power would be used to operate a relay switch.

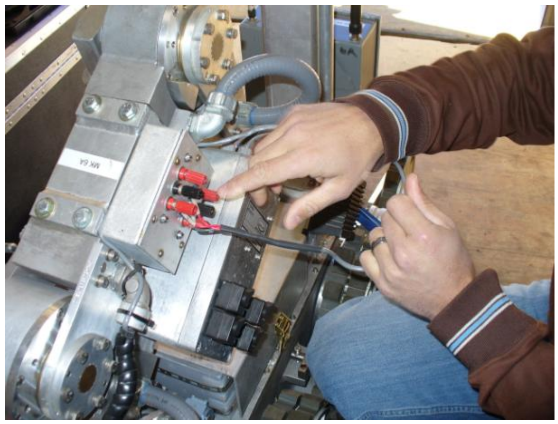


Figure 32: Auxiliary Output On ANDROS Can Turn Dervish On And Off While Down Range

An alternative was to use a bump switch. The bump switch concept was pioneered by a bomb tech and was a useful method of conserving power until down range. If the system was mounted within the gripper, closing the griper can be used to activate the switch, whereas if it was located on the outside the bump switch can be mounted on the bottom and forced against the ground to function it (Figure 33). Figure 34 (and previously in Figure 31) shows a Dervish fitted with a bump switch and mounted on the inside of the gripper to avoid interference with the disrupters. Due to the interference with other accessories an extension to the bump switch was needed in some case, so that the switch could reach the floor.

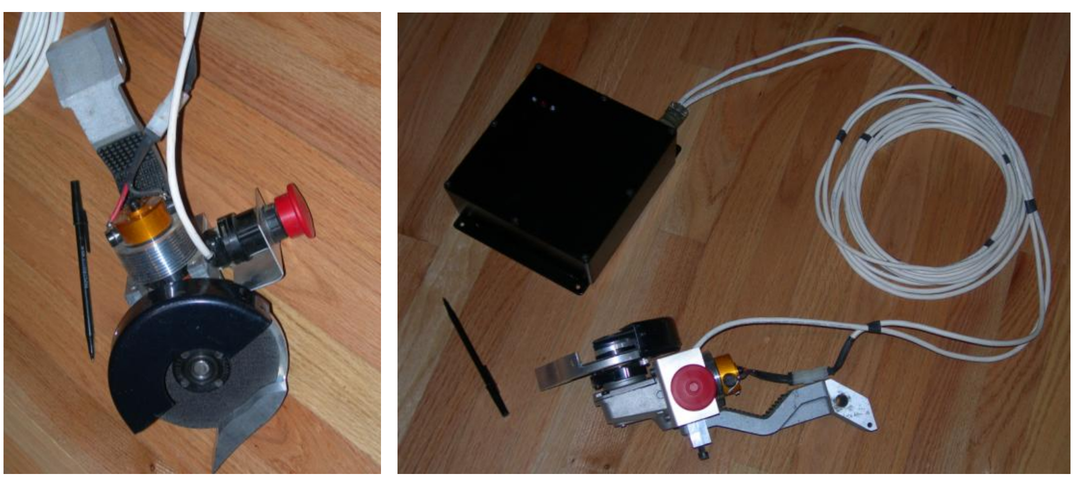


Figure 33: Dervish Mounted On Remotec Gripper Finger And Incorporating a Bump Switch For Down Range Control.

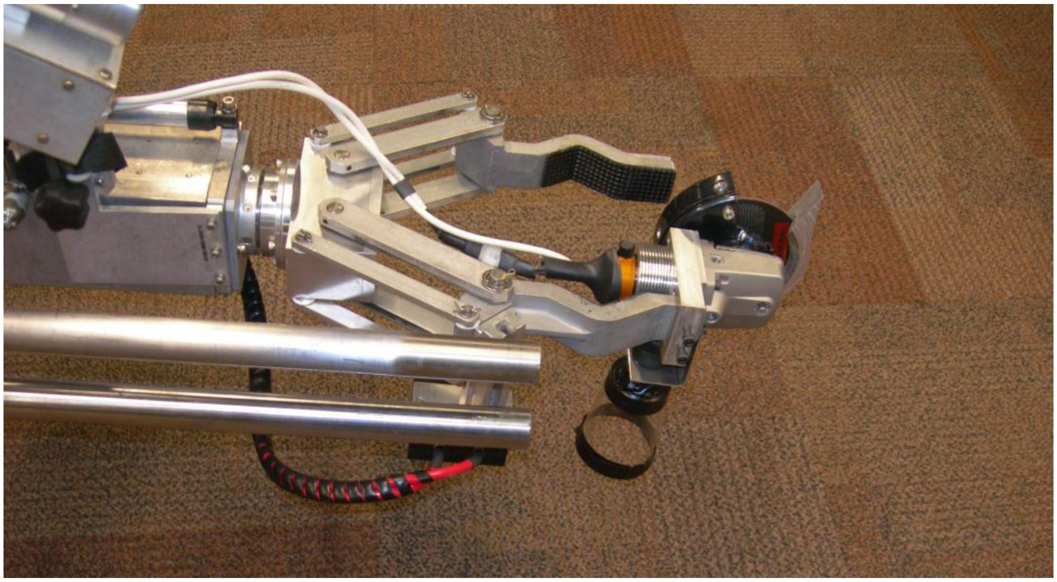


Figure 34: Floor Bump Switch With Extender

2.2.3 Testing

In addition to the bench top and laboratory testing a series of tests were performed on several EOD platforms with remote arms/manipulators to assess the system controllability. TPI also attended several IABTI conferences and the TCIP annual conferences and made several visits to manufacturers of the robots to insure that the system integrated well not only mechanically but with tactics and needs. Their comments and experiences were included in redesigns as quickly as possible and the present system represents a continuously evolving design.

A visit to the MA State Police barracks provided us with power and control take-off points, and a feel for the sight lines. The visits highlighted the differences between systems. Onboard variations included number and location of cameras and other tools that could not be blocked such as disrupters.

Presently the most common robot style was the ANDROS series, which has plenty of power, good arm flexibility, very good camera locations, and an excellent base against tipping. This means that the design has a lot of latitude for volume, weight and form factor. But the trend was towards an increased role for the smaller TALON and PACBOT class robots whose arm strength, and deck space are much more constrained. By designing with the smaller robots in mind, the overall design approach was more constrained. Our testing experience with the smaller robots was confined to the TALON.

Testing included hanging various materials such as vests, cables, and chains and cutting them off using only the OCU (non line of sight) for control. Tactical vests were hung from a chair and cut (Figure 35 and 36). Control was therefore difficult but highly realistic. Newer robots had tight arm movement, whereas the older systems were very loose and arm movement was jerky. The harder the arm was to control the more likely the system was to jam and the experience resulted in demonstrating the utility of the self reversing feature and identifying the need for an increased guide shoe footprint.

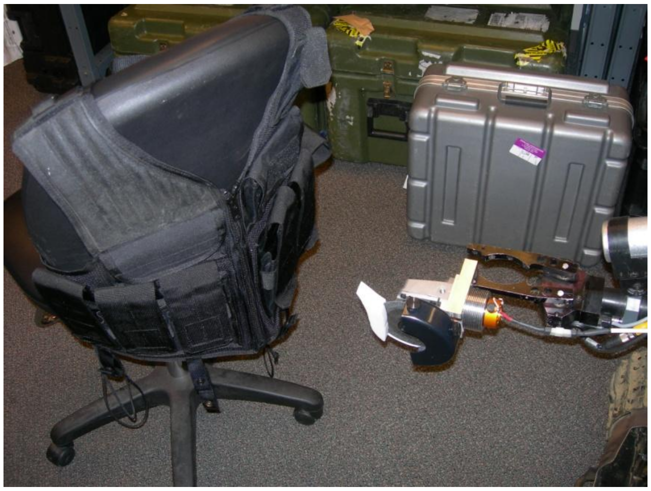


Figure 35: The TPI Cutter On The Foster-Miller TALON System Cutting A Tactical Vest Hung From A Chair.

Figure 36: Vest After Cutting With The TPI Cutter

Other observations made during testing included:

- During testing we found that the idle-to-stall bandwidth was fairly limited and could result in slower cut rates. A second generation system would have to have a higher inherent torque limit to compensate for the loss of bandwidth. A 36-V system may also provide greater bandwidth and fine tune control
- A shaft encoder would result in more accurate speed readings and be independent of threshold drift due to efficiency changes caused by motor heating. It would require more cabling, however this should be minimal.
- The motor should have a shield for the wires that incorporates the heat sinks and a fan to minimize motor heating.
- While all the vehicles have audio feedback, it was pretty poor and cannot be reliably used for additional operator feedback.
- Status LEDs were included on the electronics box that showed idle (yellow), cutting within band (green), and stall (red). The actual utility of the LEDs has not been fully realized. The operator tends to focus on the operation rather than the lights, so it not at all clear whether this would remain an important function.

- Available camera angle views were not ideal. The gripper camera only has a tilt function and no pan and cannot be twisted to best position. The mast camera zoom was better located, but the gripper blocked the view. Putting the cutter on the left side (same side as the mast) might improve it but the cutter body would block its view. The best positioning for the cutter would require a couple of days operating on the various robot systems.

As a result of these user trials the following engineering/design issues were identified as requiring attention in the Phase II effort:

- ***Able to drop off, pick up tool:*** One goal was the ability to use the cutter, drop it on the ground and then pick it up again so that the gripper could do other functions without needing to drive back to the command point for a tool change-out. This would require vehicle specific mounting bracket design and testing. Operationally a key design consideration would be whether the 6 ft power cord was sufficient to drop the tool and continue the operations, or do we need to completely separate the power cord during the drop off phase.
- ***Door breaching:*** The robots are often shared with the SWAT teams who need to cut through door locks, suggesting need for a door breacher. The cutting action and control were the same as the base Dervish and the control algorithms would be directly applicable. The cutter wheel however would need to be increased in diameter, and a higher torque motor maybe required. Present cut depth was limited by the cutter wheel diameter to 1-in and a 3-in depth of cut would be required to meet most door dimensions.
- ***Better bump switch:*** Presently the bump switch was a push-for-on and pull-for-off with the result that it cannot be turned off other than manually. A more flexible design and extender method was needed.
- ***Mounting on other robots:*** The Dervish was essentially designed for the ANDROS, with its wide gripper fingers, but there was interest in the TALON and PACBOT whose gripper fingers are svelte. The lack of meat on the gripper would be challenging to establish a steady mount and maintain the ability to pick-up the tool while down range. We also may have to reduce the weight of the head so the older small units can carry it. In theory the arms are strong enough to carry the 4-lb weight (since they are rated at 7-lb) but experience shows that the rating may be optimistic.
- ***Switchable batteries:*** Presently the batteries are integrated with the electronic box and can only be recharged with a dedicated cable. If a standard battery set could be found to meet the requirements, it would enable the batteries to be removed for recharging and a spare set used to continue the mission. The down side was that commercial batteries have built in safe guards and recharging circuitry that could limit the current draws and confound the control circuitry. It would also require an additional piece of equipment or recharger. The electrical protection fuse was also inside the box and needs to be more accessible. It also may be useful to go to 36-V (it is presently a 24-V system) so we get more control. We can lighten up the system or reduce volume using lithium batteries, but the charging control becomes a challenge.
- ***Ability to switch out and use drills, rug cutters:*** The basic capability offered by the tool with closed loop feedback was a useful one, and there has been interest in switching out the tool head depending on the mission. Heads would include drills, hole saws, and rug

cutters. The rug cutters can fit on the existing system but the arbor hole for the blades have to be changed since the grinder and the cutter hole diameters are different.

- ***Swivel guard:*** Presently the guard was manually fixed before the mission. We might want to look at a sliding shield similar to a circular saw. This would add complexity and weight, but would provide a great deal of control flexibility.
- ***Hand carry:*** Some of the operators liked the idea of being able to hand carry and operate the cutter (no robot).
- ***Aiming guides:*** Aiming guides on the guide shoe and cowl would give the operator visual aiming reference points of where the blade was and where the contact tangent was for easier control.
- ***Motor cowl:*** A rugged housing for the motor was needed so that the system could incorporate its own fan and the wiring was covered and protected
- ***Higher torque motor:*** The control algorithm protects the system by setting a current threshold just below stall to kick in the auto-reverse and provide the anti-jamming feature. But a lower threshold was just that and the operating speed and torque was reduced resulting in less power/aggression than a hand tool (which was instantly controlled by the operator). A higher torque motor would return the power loss due to a lower threshold. An expectation of the cutter was that it would out-perform hand units. It does for a control, but it's not faster, and the operators want faster.
- ***Lighter head:*** If we go to PACBOT and TALON, the brackets, shields and maybe even the gearing needs to be lightened up. The overall system weight can probably be reduced by 25% at some commensurate reduction in ruggedness and durability.
- ***Encoder:*** The present system uses the back-generated voltage to monitor blade speed which was nice because it does not require any sensors, The problem was that as the motor gets hot the amount of back generated voltage changes and so our threshold was essentially changing. If an independent shaft encoder like a Hall effect sensor was added, the control would be rock solid.
- ***36 V:*** If we go up to a 36-V system it will provide more baseline power and speed plus allow more bandwidth to fine tune the operation. 36 V was also the trend for most battery powered systems (for the same reason) and we would therefore be compatible with more robots and tools.

2.3 Summary Of Phase I

The NIJ funded Dervish met its primary Phase I objectives.

The Dervish is a cutter attachment for legacy EOD robots designed to cut through cloth, ballistic nylons, mixed textiles with zippers, buckles, zippers or chain, key shanks, and cables; all with a single tool. A shoe-guide prevents damage to the surface. High efficiency motors, a closed loop feedback and auto reverse prevents mission ending lock-up, and increases mission life significantly. The separate cutting head provides a light tip load and low physical profile and battery and control electronics are located on the robot deck to maintain proper vehicle balance free up vision and other mission functions such as gripper or disrupter line of fire.

The Dervish can be turned on by a bump switch, or activated by hooking into accessory ports found on all robots. The Dervish was independent of the robot control system and does not require any additional software or control interfaces and it was positioned by the operator using standard controls. Indicator lights alert the operator through the robots existing on-board cameras as to whether the cutter was idling, cutting, or about to stall. If the cutter stalls, it reverses and begins again. The cutter speeds and torque thresholds can be optimized for different materials through an external switch.

3. Phase II

The starting point for Phase II was the Phase I Dervish prototype:

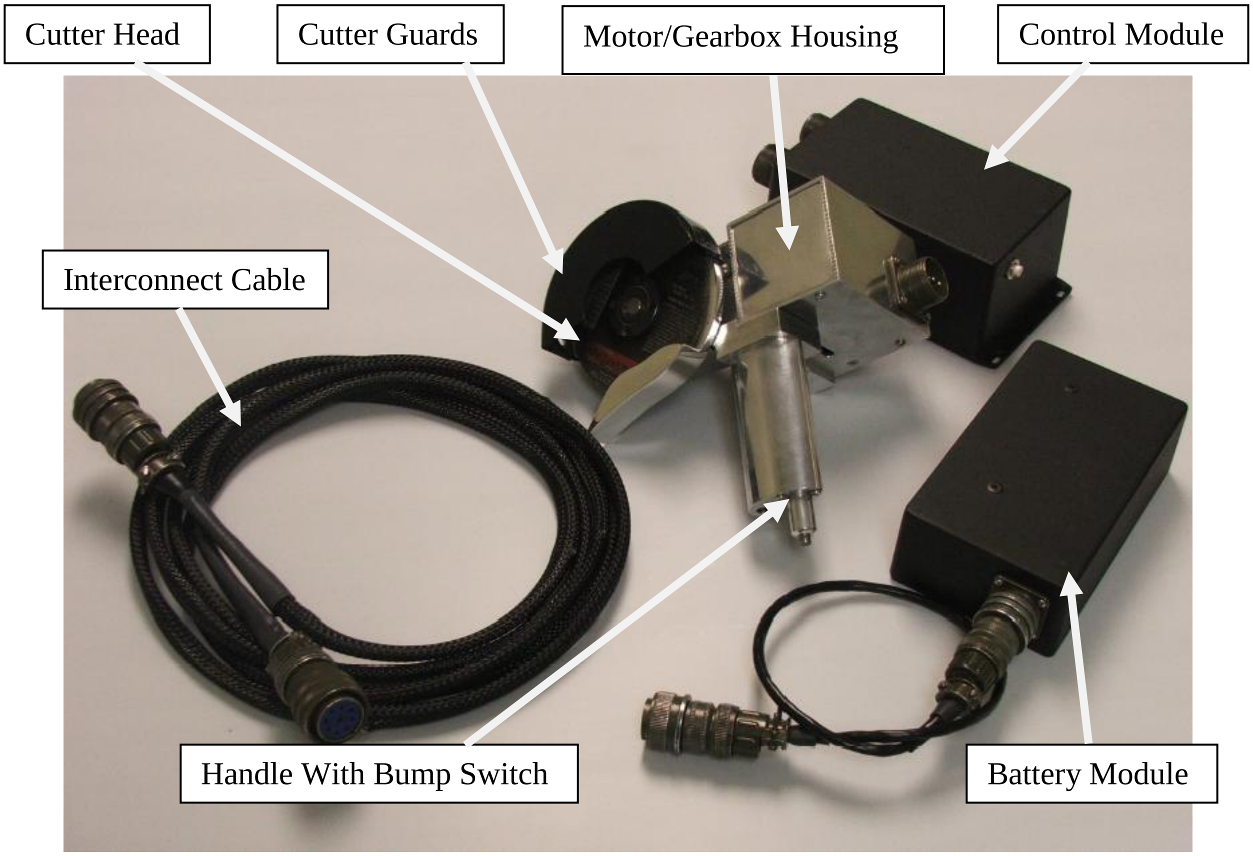
- Fits legacy small and large robots
  - Carries own battery power
  - No control software required
- Self compensating control makes operation easy
- Cutter head separate from electronics and battery
  - Light gripper weight
  - Low physical and visual profile
  - Fits small robots
  - Maintains balance
- Doubles as hand held power cutter
- Has safety shoe for operation on humans
- Holds cut-piece in-place
- Cuts mixed materials; tested; 9/32" lock (Master), 3/8" aircraft cable, Hand cuff, tactical vests 5 layers thick; buckles, zippers and Velcro
- Auto-reverse when jamming prevents circuit and battery burnout and eases operator workload
- High efficiency motor, low idle speed; improves mission life by 500%
- Kerf .045", 1-in deep cut, 13,300 rpm
- No sensors to break – sensing done between battery and motor – no additional wires
- Down range bump on-switch
- Head 4.13 lbs; E- box with batteries 6.38-lb; Total 10.5-lb
- 6 ft cable for battery/electronics
- Status indicator lights for supplementary visual feedback

Phase II was a much smaller effort than Phase I with objectives of enhancing the original design with improvement identified during testing and of making the unit more 'field ready' and suitable for significant user trails.

Over the course of the Phase II TPI actually completed two design iterations (Figure 37). Both will be covered in the sections that follow in an integrated manner to describe both the end product and the logic of the development process that arrived at that final design.

3.1 Phase II Enhancements

The following sections describe the design/integration features that were addressed in the Dervish project under the Phase II contract.



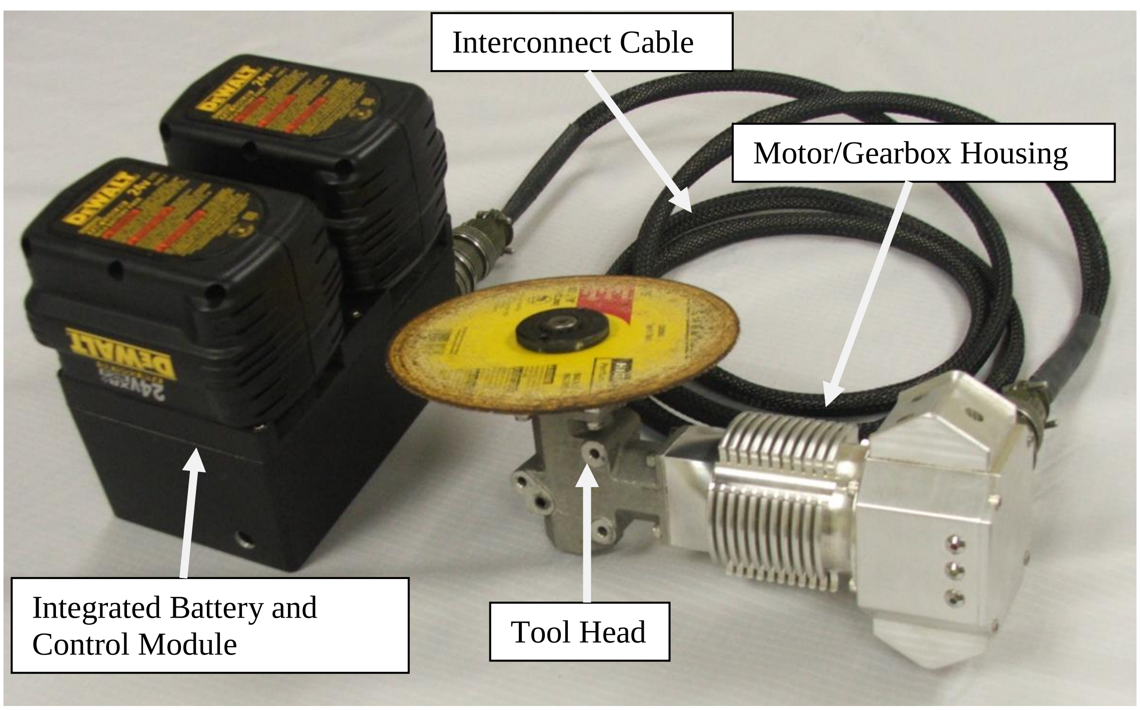


Figure 37: During Phase II Two Very Different Design Iterations Were Developed.

3.1.1 Ability To Drop Off, Pick Up Cutter

A major goal of this development was the ability to use the cutter, drop it on the ground and then pick it up again so that the gripper could do other functions without needing to drive back to the command point for a tool change-out. The ability to drop off and pick up the tool is directly affected by the design of the tool handle. This feature was currently a function of 'generic' gripper characteristics, integration of the control switch, and to resist tool generated torque during use. In the first Phase II Dervish the handle has a simple ellipsoid cross-section as seen in Figure 37. This allowed any multiple finger gripper to hold the tool. If the tool was 'dropped' or placed in an on-board holster then the gripper should be able to pick it up again for a second cut. The second design variant actually incorporates platform specific gripper interfaces that ease this gripping task. The tailoring of the external Dervish features to interface to specific OEM platforms and manipulators was discussed in Section 3.2 below.

Operationally a key design consideration would be whether the 6 ft power cord was sufficient to drop the tool and continue the operations, although an option exists to completely separate the power cord during the drop off phase and to develop a simple plug-in connector to allow the manipulator to reconnect the two halves at a later point in time. This task was not executed during the current effort.

3.1.2 Door Breaching

This was another big interest from users during demonstrations of the Phase I design. The robots are often shared with the SWAT teams who need to cut through door locks. Door breachers mounted to EOD and tactical robots have been demonstrated before on OEM robots such as the FMI TALON in Figure 38 but the tool has not been implemented in the modular fashion of the Dervish.

Figure 38: Door Breachers Have Been Implemented On Robots Before But Only As Semi-Permanent Integrated Tools.

The function and control of the larger cutter was the same as the original Dervish and the control algorithms would be directly applicable. The cutter wheel however would need to be increased in diameter, and a higher torque motor may be required. Present cut depth was limited by the wheel diameter to 1-in. For breaching a 3-in depth of cut would be required. A new higher torque motor operating at higher voltages was selected to support this tool and is discussed in more depth below. Figure 39 shows the latest Dervish variant fitted with a larger (8-in) breaching wheel.

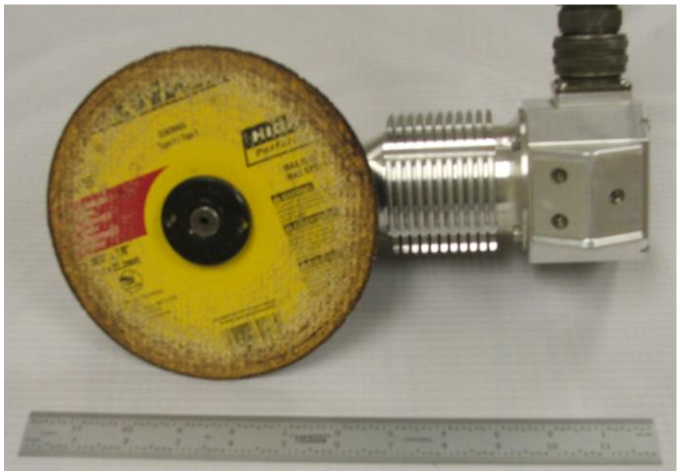


Figure 39: The Dervish Tool System Configured With A Door Breacher Cutting Wheel.

3.1.3 Better Bump Switch

The Phase I bump switch was a push-for-on and pull-for-off, with the result that it cannot be turned off other than manually. A more flexible design was needed. That original design also carries battery power all the way up to the cutter head, back to the electronics and then back to the motor. The Phase II plan was to change controlling the on/off function to utilize a relay as part of the electronics thus eliminating ½ the voltage drop across the cable to-from the cutter motor. We also replaced the Phase I 'E' stop type switch with a "push on push off" momentary switch (Figure 40). This approach opens the opportunity to mount more than one switch to allow easier access for remote on/off actuation (say on the bottom and side of the cutter head). Also, since all of the robots use a gripper mechanism another concept pursued was for the on/off switch to be controlled by pressure applied by the robots gripper, when the tool was released by the gripper it shuts off. The final mechanical switch we considered was a whisker switch (touch-on/touch-off) to obviate the need for close contact between the cutter and a hard surface. The whisker switch could even be mounted on the robot platform and actuated by the manipulator arm brushing against it. In addition to a mechanical push-on/push-off switch we explored implementation of a proximity switch that turns the cutter on when it approaches the material to be cut and disengages when the cutter moves away from the material thus shutting off the power to the cutter to extend battery life. These switch options are shown in Figure 41:

- Hardened 'Bump' switch mounted on tool – robot hits tool against wall, ground, chassis to start/stop tool
- 'Whisker' switch mounted on platform – robot hits whisker with arm to start/stop tool
- Proximity switch – robot moves flag close to switch to start/stop tool.

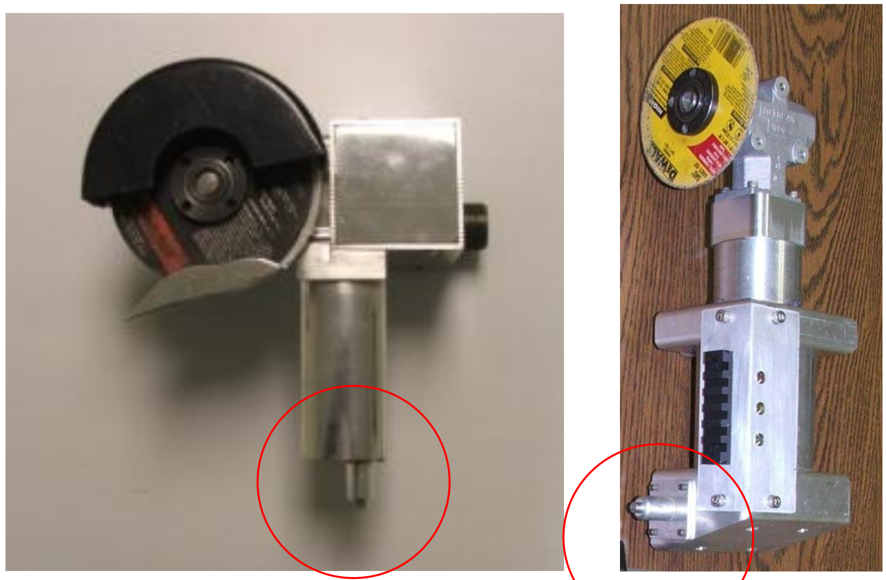


Figure 40: A Bump-On/Bump-Off Switch Integrated Into The Tool Handle Is One Simple Control Approach

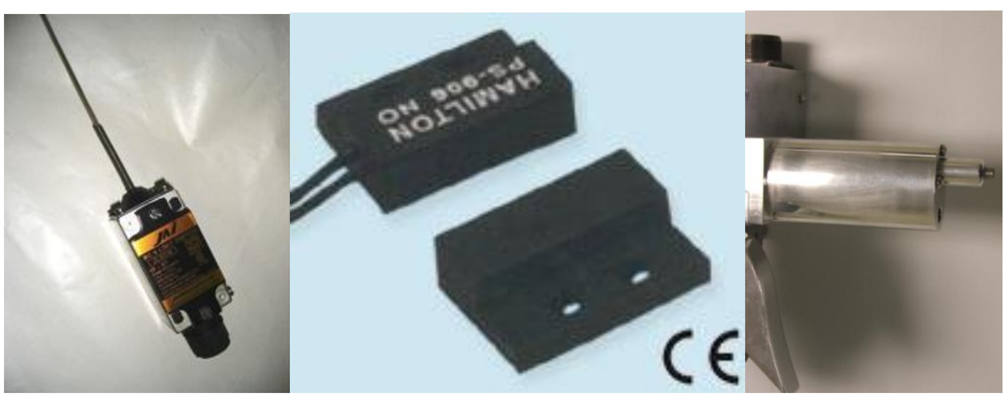


Figure 41: Multiple Control Switch Options Were Reviewed.

The other option, which would work with some platforms but not all, was to tie into the onboard control electronics and to have the Dervish switched from the OCU. Figure 42 shows this option for the ANDROS platform.

3.1.4 Modular Battery Pack

In the Phase I design the batteries were integrated with the electronic box and could only be recharged by dismounting the whole system and plugging in the recharge cable. If a standard battery set could be found to meet the requirements, it would enable the batteries to be removed for recharging and a spare set used to continue the mission. The down side is that commercial batteries have built in safe guards and recharging circuitry that could limit the current draws and confound the control circuitry making the charge/high current discharge cycling difficult to manage. It would also require an additional piece of equipment, being a separate recharger.

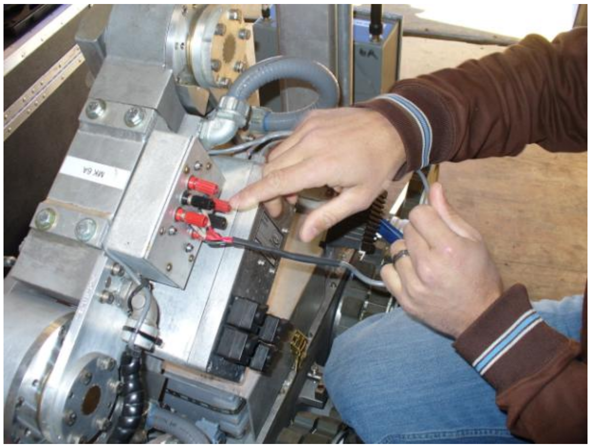


Figure 42: Some Platforms Offer The Option To Switch The Dervish On And Off Via The OCU.

Finally, in the original Phase II design the electrical protection fuse was inside the housing and difficult to access – it needs to be more accessible.

In an effort to evaluate the modifications required for optimum performance with different platforms and with the option to ‘feed’ power from the base platform we modified the Dervish power circuitry to support use of multiple battery voltages. This would make the system more flexible allowing for the use of robot power or battery packs with more power for more demanding applications such as door breaching. Battery packs are available using different technologies in the 3 voltages we plan to use (24, 36 and 48-V). A set of dip switches would allow the user to select the battery pack appropriate to the mission/robot. Each technology has its own advantages and disadvantages. Based on cost and efficiency we prototyped 48Volt NiMH battery packs as the default power source (Figure 43) for the first variant of the Phase II Dervish.

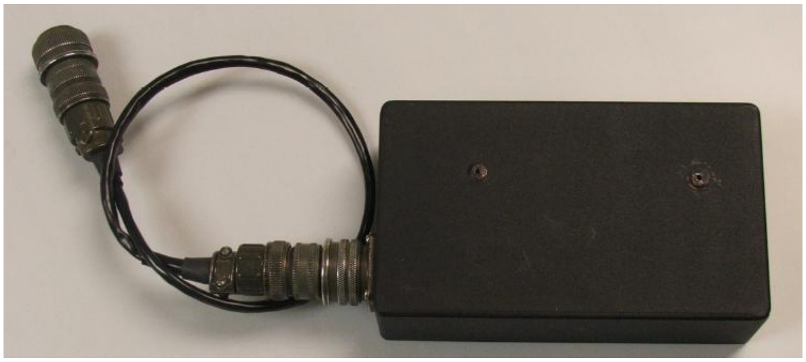


Figure 43: A 48-V Battery Pack Supports High Power Draws And Longer Missions.

These higher voltages required the use of a battery charger designed specifically for charging these batteries. For Dervish, this battery pack would be packaged in a cast aluminum enclosure with a single connector which would be used to connect the battery pack to either the tool or to the battery charger. The length of the cable that attaches the battery to the tool would be dictated by what makes sense for the particular robot being used. Battery packs of different voltages would be different sizes and weights so their enclosures would be different as well.

At the same time we revisited the option of using COTS battery packs from the commercial-industrial cordless tool market. The highest voltage commonly available pack at this time was 24-V with some 36-V units available. We compared the capacity of these power sources and the custom packs discussed above against the Dervish draws at that voltage (Figure 44):

- Power Draws @ 24-V
    - Idle – 3A
    - Full speed, no load - 8A
    - Full load – 16A
- COTS cordless power tool batteries (24-36-V @ 2.4 – 3 AH) = 9-min cutting (3-lb)
- Custom battery pack (24 – 48V @ 10 AH+) = 37-min cutting (10-lb)

Figure 44: We Compared COTS To Custom Battery Pack Performance.

While 24-V was the most common COTS pack, 36-Vwould provide more bandwidth to fine tune the operation. 36-V is also the trend for most future battery powered systems, both tools and robot platforms (for the same reason) and we would therefore be compatible with more robots and tools. These COTS battery packs, naturally, all come with 'quick' chargers and offer the potential to be used either in their COTS housing or for the battery packs to be stripped out and rehoused while still being usable with the intelligent chargers (Figure 45).

Figure 45: COTS Batteries Come With Smart 'Fast' Chargers And Can Be Used In Original Housings Or Stripped Out And Repackaged.

After a review with the user group it was decided that a COTS based approach would be preferred as it provided the most flexibility for battery replacement while allowing sufficient cutting time for most missions. The option of using multiple batteries (2-3) in parallel to provide longer cutting time addresses mission life concerns and was an easy field connectable option. With this in mind then TPI rehoused the tool interface used with a high end COTS battery (the DeWalt 24-V unit) onto the top panel of the Dervish electronics box so that the COTS battery merely slipped onto as if it were connecting to a tool. As shown in Figure 46 we actually configured the unit with two battery interfaces to maximize cutting time. This approach was applied to the second Phase II Dervish variant. This approach also allows the user to utilize standard chargers.

Figure 46: COTS Batteries Mount To The Dervish Electronics Box Through Their Standard 'Tool' Interface.

3.1.5 Swivel Guard

In Phase I the guard was manually fixed before the mission. We reviewed the option of a sliding shield similar to a circular saw (Figure 47). This improvement was really only of value when Dervish used as hand tool but complicates remote cutting operations since it requires correct orientation and fairly precise positioning of the edge of the guard relative to the target. This option was not pursued further.

3.1.6 Useability As A Hand Tool

Some of the operators liked the idea of being able to use the cutter as a hand tool. With the electronics and battery box tethered the 'in-hand' tool weight was minimal. With a combination of smart electronics and the manual dexterity of the operator the Dervish would perform at least as well as a standard hand tool. While the ergonomics of either of the two Dervish variant bodies are not optimized for hand use (Figure 48) they do allow occasional, short term by-hand use.

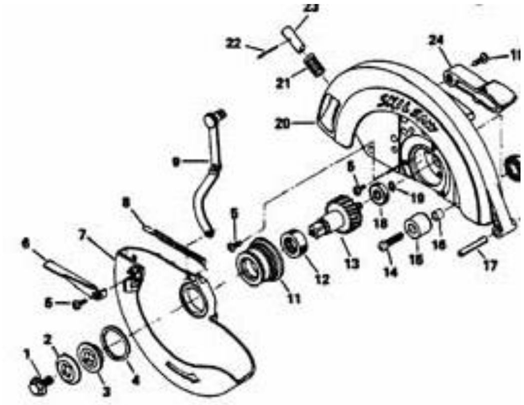


Figure 47: A Circular Saw Type Swivel Guard Complicates Remote Cutting As It Requires Correct Orientation Relative To The Target If It Is To Work Correctly

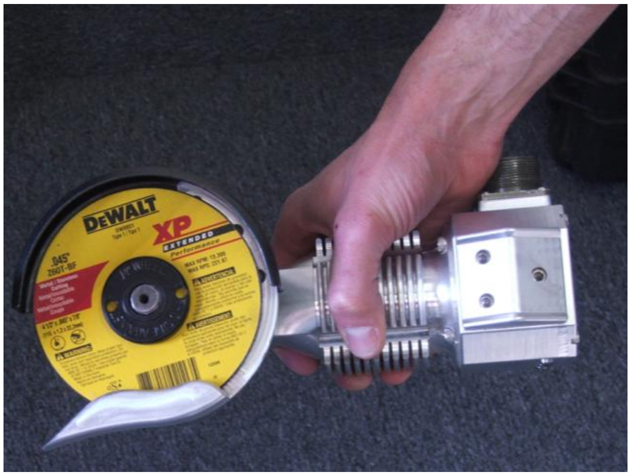


Figure 48: While Not Optimized For Hand Use The Low In-Hand Weight Means Either Dervish Can Be Easier To Utilize Than Conventional Tools For Short Occasional Uses.

3.1.7 Aiming Guides

Aiming guides on the guide shoe and cowl would give the operator visual reference points observable through the standard video system on the robot platform of where the blade was and where the contact tangent was for easier control. A line laser similar to that on high-end circular saws (Figure 49) would be a good candidate for this role. This option was not evaluated in this project but would be a fairly easy modification in next generation units.

3.1.8 Motor Cowl

A more rugged housing was needed than either the Phase I or early Phase II configuration to protect the system and wiring. This mechanical detail was driven in part by the final selection of the motor and the mounting configuration. As seen in figure 50 the later system configuration was much more rugged than the earlier Phase II housing.

Figure 49: A Line Laser Could Be Used For Target/Blade Orientation Visible Though The In-Place Platform Video System.

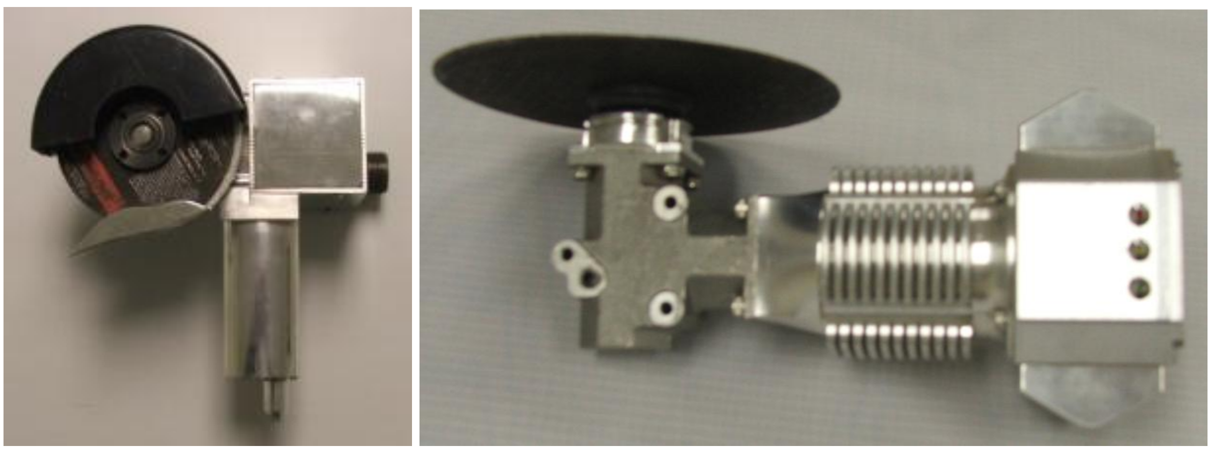


Figure 50: The Second Phase II Design (Left) Is Much More Rugged Than The Early Version (Right)

3.1.9 Higher Torque Motor

The control algorithm protects the system by setting a current threshold at just below stall to kick in the auto-reverse and provide the anti-jamming feature. This threshold reduces top end operating speed and torque resulting in less power/aggression than a hand tool (which was instantly controlled by the operator). A higher torque motor would return the power loss due to a lower threshold. An expectation of the cutter was that it would out-performs hand units, which it does from a control perspective, but the Phase I unit was not faster - and the EOD technicians want faster.

A new high power motor (Figure 51) was selected. It provides more power than the previous motor at 24-V and would operate all the way up to 48-V. It comes with a 2.75 to 1 gear reduction. This provides for 4400-rpm @ 48-V and 80-in-oz of torque as opposed to 17500-rpm

@ 18-V and 25-in-oz of torque provided by the original motor. The higher torque allows that more pressure be applied to the cutter without it stalling.

Figure 51: Dervish Was Upgraded To A New High Power, High Torque Motor (Top Motor) With Integral Gear Reducer.

3.1.10 Lighter Cutter Head

The major weight contributors to the cutter head are the motor/gearbox and the ruggedized housing. The mission drives the power pack design so assuming a similar mission for the small robots as the large that item cannot easily be changed. If we need to support PACBOT and TALON sized platforms then the brackets, shields and housing need to be lightened up. The overall system weight can probably be reduced by 25% at some reduction in ruggedness. This approach can be pursued in follow on work if this market was to be addressed.

3.1.11 Control Via Encoder

The present system uses the back-generated voltage to monitor blade speed which was desirable because it does not require any external sensors, The problem was that as the motor gets hot the amount of back generated voltage changes and so the threshold was essentially changing. If an independent shaft encoder like a Hall effect sensor was added, the control would be rock solid. The issues here are cost, wiring and control complexity. The encoder needs power and signal lines run to connect it to the electronics box. We need processing hardware and software to interpret the output and generate a corresponding control algorithm for the drive system. While a more sophisticated approach the complexity may not be warranted. We have not seen the need for better control during our testing but if after user trials this deficiency was indentified it can be corrected in next generation units.

3.1.12 Auto Reverse

Even with the cutter power/torque feedback the potential still exists for the cutter disk to jam in a fabric or other target material. This stall effect would very quickly drain the battery and could result in permanent damage to the motor and controller. As described previously in Section

2.2.2.4, during Phase I TPI developed and integrated an auto-reverse functionality into the device controller whereby if it jams and stalls it automatically reverses to extricate the blade from the material then reverts back to forward to allow the operator to continue cutting. This feature has been retained in the Phase II devices.

3.1.13 Status LEDs

The status LEDS that, in Phase I were mounted on the electronics box were moved in Phase II to the rear of the actual cutter assembly so that they can be observed through the platform, cameras. Figure 52 shows both Phase II variants with these LEDs.

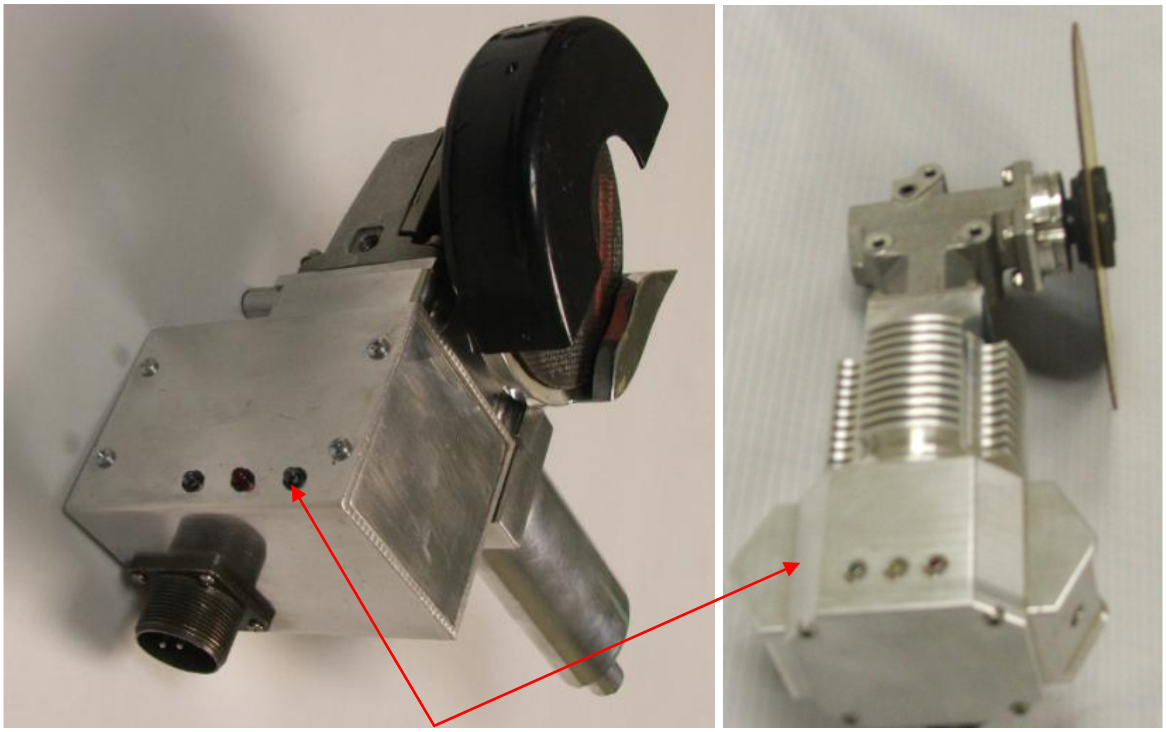


Figure 52: Status Indicating LEDs Have Been Relocated So As To Be More Visible To The Operator Through The Normal Camera View Of The Robot Gripper

3.1.14 Mounting On Other Robots

The Dervish was originally essentially designed for the ANDROS but there are several viable platforms in the market place. As stated previously, the manipulators on all of these platforms have opposable fingers which allow them to grip the first Phase II variant with the pistol grip handle. Also as discussed above that configuration had limitations in respect to the ability of the grippers to resist the torque generated by the tool as it cut and therefore for the manipulator to hold the cutter on target. The main attraction of the design was its universal applicability.

Under review, the value of this universal nature became reduced. The reality was that most user groups have only a single type platform in use, or have ones dedicated to recon and interdiction etc whereby having a Dervish more customized to a specific platform, and therefore more capable when on that platform outweighed the advantage of being able to swap it out instantly between platforms. With this in mind, the second Phase II variant was designed with the concept of a central power head with modular add-on features to support better mechanical interface to the host platform. At the same time these add-on features were interchangeable allowing the unit to be used with multiple platforms but just not in an 'instant' mode. The Dervish was thus configured a s common cylindrical power module onto which are added platform specific mounting interfaces (as shown in Figure 53).

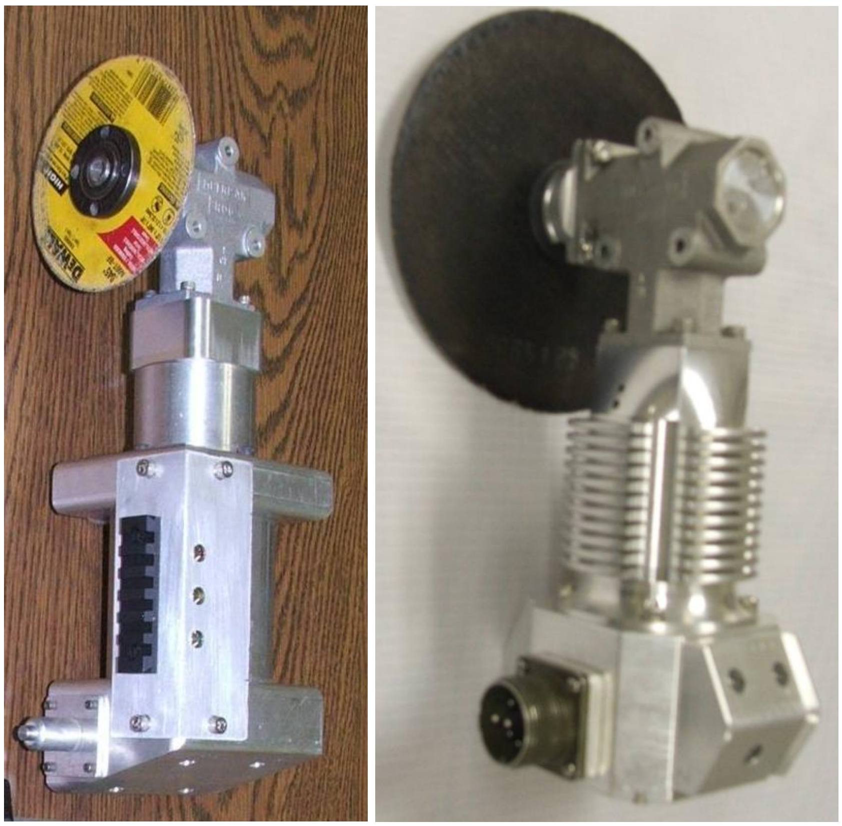


Figure 53: The Basic Power Unit Is The Common Module With Add-On Features To Interface To Specific Platforms (Landshark on left, ANDROS on right).

TPI configured the second variant to work with multiple demonstration platforms. Specifically we configured deliverable units optimized to work with both the Black-I Robotics Landshark and the Remotec ANDROS.

Figure 54 shows the Dervish configured for use with the Landshark platform. The features integrated into the body lock it into place against hard stops that are already features of the manipulator:

- A tang on the bottom face of the Dervish fits between the two fingers on the lower manipulator
- The flat back of the Dervish butts up against the flat back of the inside of the manipulator
- The two upper fingers of the manipulator hold the Dervish in place.

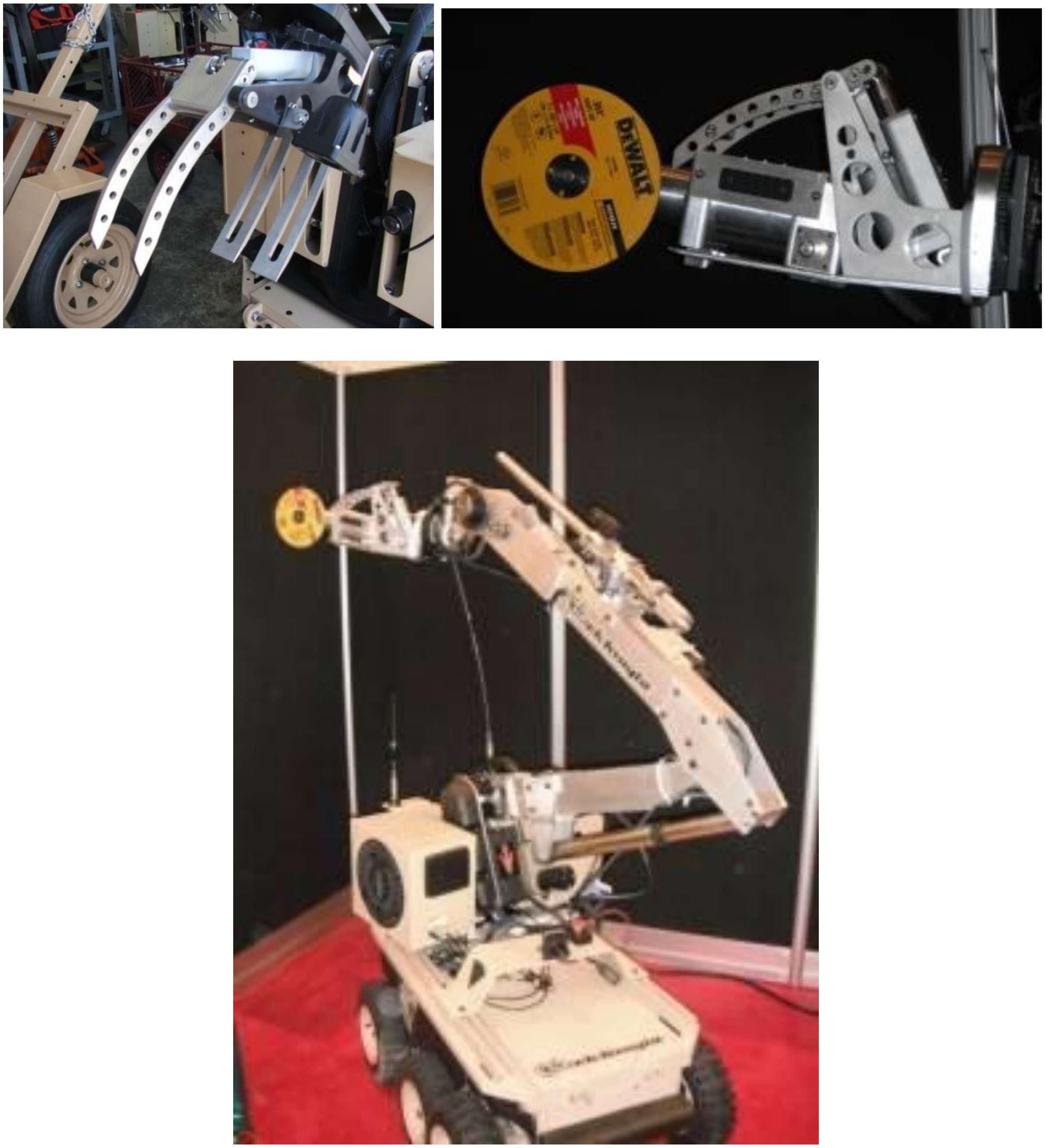


Figure 54: The Dervish Power Module Was Fitted With Adaptors To Match The Landshark Manipulator.

Figure 55 shows the Dervish configured for the ANDROS. In this case the unit has mounting blocks configured to match the interior features of the manipulator fingers, specifically the angled V on each side.

As an additional design exercise, and to address the potential application to smaller robot platforms, we developed an interface kit for the TALON manipulator. Figure 56 shows that system (with Dervish fitted with a reciprocating saw tool head – see Section 3.1.15 below)

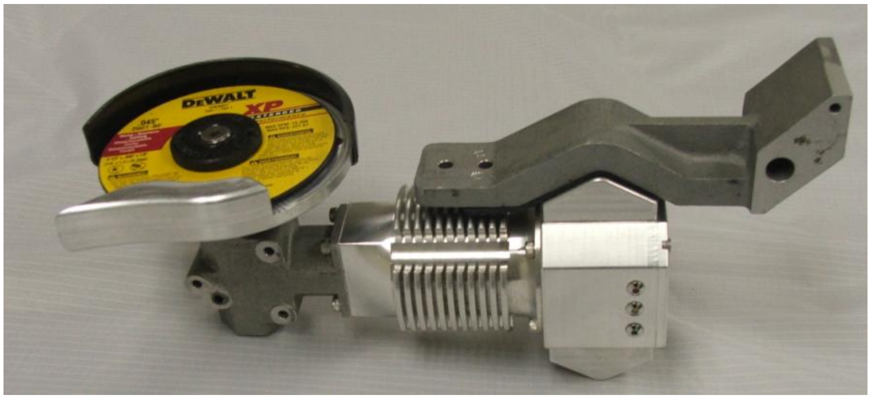


Figure 55: The Dervish Mounting Blocks Can Be Configured To Match The Interior Features Of The ANDROS Manipulator.

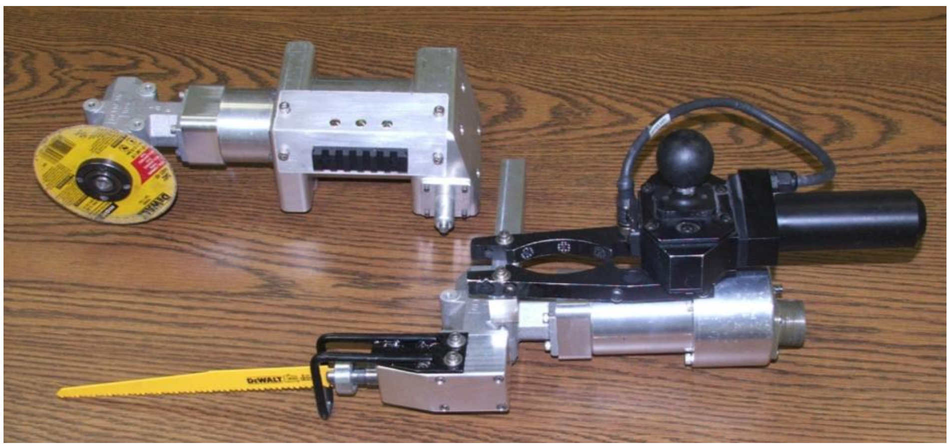


Figure 56: The Dervish Power Unit Fitted With A Landshark (top) and TALON (bottom) Manipulator Interface Kit (And Reciprocating Saw Discussed In Section 3.1.1.5).

3.1.15 Ability To Switch Out And Use Drills, Rug Cutters

The basic capabilities offered by the generic tool with closed loop feedback are useful ones, and there has been great interest in an ability to switch out tool heads off of a base power module. Heads could include drills, hole saws, and cloth cutters depending on the mission. This approach has been applied to both conventional power tools (Figure 57) and in a simplistic manner to on-robot tools (Figure 58). The tools in Figure 58 are completely conventional battery powered tools that are wrapped in a holding bracket that interfaces to the robotic arm. This approach takes advantage of the great range of battery powered tools available but does not provide any mission or platform specific tailoring of the tool capability – this results in very much not optimized performance.

TPI's approach was to use the basic Dervish power unit with its intelligent controller and highly flexible power system and to develop a family of easy-on/easy-off tool heads (Figure 59). The operator could select from a small (4 1/2") cutter, a large (8") cutter/breacher, a drill, or reciprocating saw, install the tool onto the power head and then deploy the robot down range.

Figure 57: COTS Systems Are Available That Feature Interchangeable Tool Heads For Drills, Reciprocating Saws, Grinding Wheels, 'Roto-Zip' Heads And Vibrating Sanders.

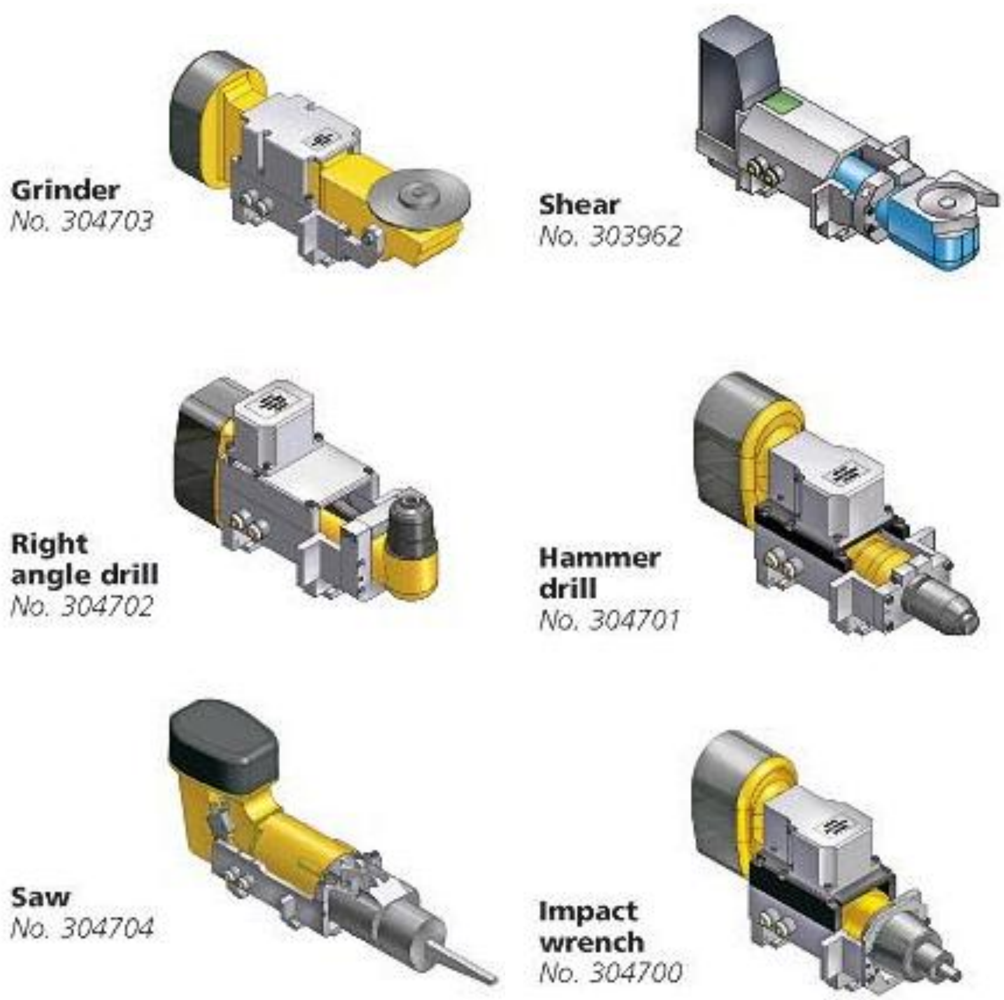


Figure 58: One Approach To Multiple Tools Is To Just Add A Mount Adaptor To Conventional Tools – The Downfall Is Very Non-Optimized To Mission Performance.

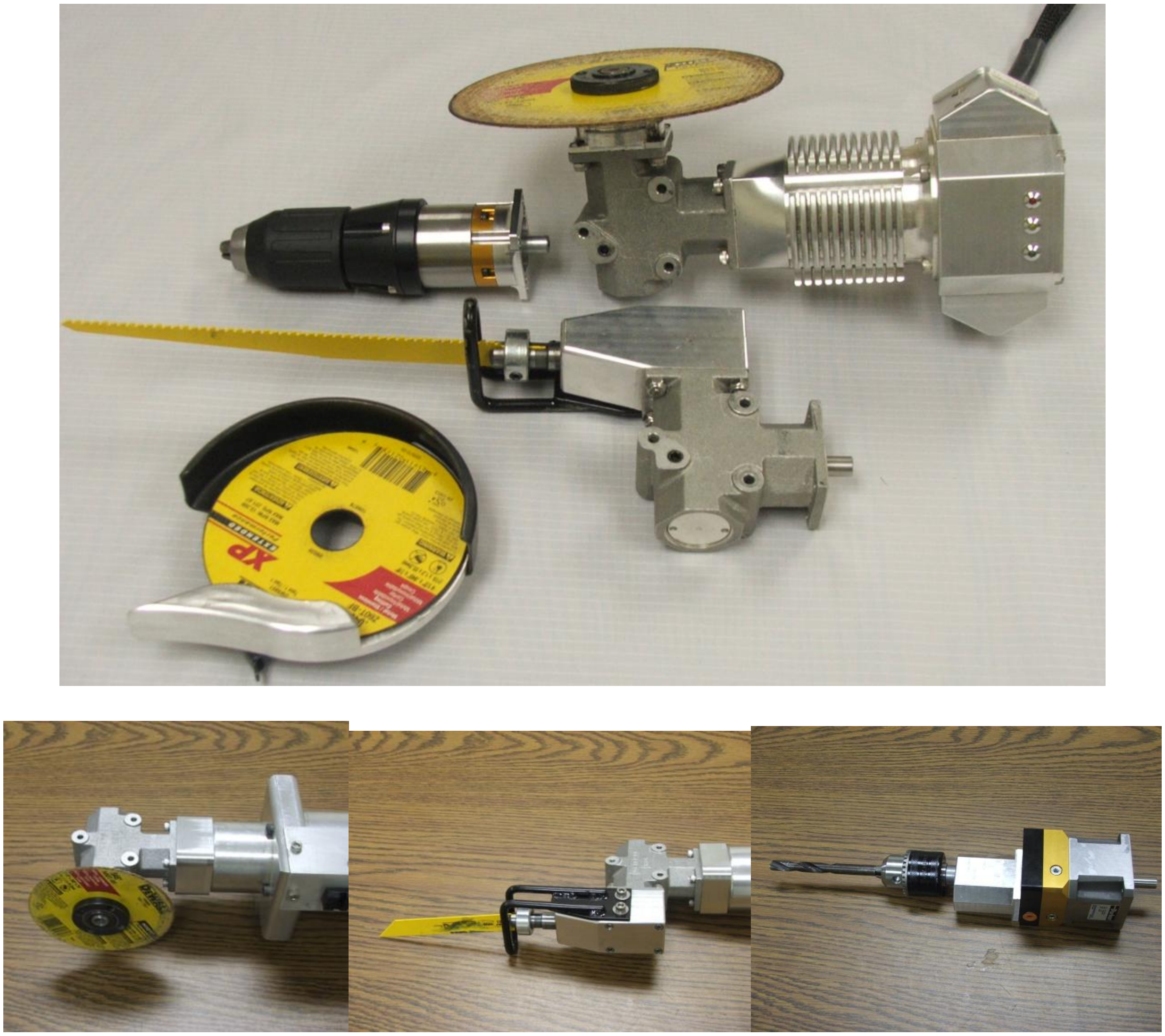


Figure 59: The Core Dervish Power Unit Can Be Fitted With Small Cutting Disc, Breaching Disc, Reciprocating Saw And Drill.

3.2 Summary Of Phase II

In Phase II of the Dervish program TPI successful achieved the objective of enhancing the Phase I device and maturing it into a system ready for significant user trials. The Dervish as now configured offers the user great capability to manipulate down range structures and items in an efficient flexible manner. The user can cut, saw and drill targets with a platform independent highly operationally flexible device. That device would not jam and can be tailored to multiple platforms and missions.

Phase II final Dervish component weights are:

- Controller Electronics – 2.5-lb
- Drive Unit – 2-lb
- Cutter Head – 1.75-lb

- Saw Head – 1-lb
- Drill Head – 3-lb
- Cable (6-ft) – 2-lb
- Battery (24-V, 10-Ah) – 10.5-lb
- Platform mount adapter – 1-2-lb
- Total Arm end weight (Drive + Tool + Adapter) = 4-7-lb

This system was ready for extended field trials.

Unfortunately the severe funding limitations on Phase II precluded the completion of the extensive field and user trials originally envisioned. The Dervish system was however demonstrated or exhibited at several conferences for the International Association of Bomb Technicians and Investigators (IABTI), US Bomb Squad Commanders and Technology for Critical Incident Preparedness (TCIP) organizations with a very positive reception.

3.3 Post Phase II Development

Based on the level of enthusiasm expressed for this product in the limited feedback obtained from the exhibitions detailed above and from working with several EOD robot platforms manufacturers, Technical Products Inc., committed to the development of another generation of Dervish system. This internally funded R&D was out of scope of the NIJ contract but is reported on here as it is a natural follow on to the Phase II effort described above and as it should be of great interest to the readers of this report. To separate this work from the contractual effort, it is reported on as a stand-alone addendum to this report, Appendix A.

APPENDIX A

The Technical Products Inc., 'Phase III' Dervish Development

While the Phase II Dervish device discussed above worked well and demonstrated the capability to meet the minimum performance required of it, it suffered from three limitations that would detract from its 'marketability':

- it was a mechanically complex device to assemble (which translates into cost)
- it was marginal at performing hard cuts requiring high power draws over an extended period
- the design did not scale well between a larger high capacity device for large robots and a smaller, potentially lower cutting capacity system for small platforms

Since the development of a product that would be adopted by the user group was the overarching goal of the program, these issues were of concern to TPI. In order to better 'productize' the Dervish TPI undertook the development of a third generation system.

This generation of Dervish shares many of the key attributes of the Phase II device:

- Smart control software that supports:
    - No-load run at low speed idle mode
    - automatic adjustment of power supplied to cutting load
    - automatic sensing of near stall condition due to jam with automatic motor reverse to free jam
- Utilizes standard DeWalt 24-v DC battery packs
- Utilizes standard DeWalt battery chargers
- Utilizes standard cutting disks
- Incorporates a disk guard for safety when used as a hand tool and for cutting garments off human targets

The major change implemented was the selection of a new motor/main drive system. The motor used in Phase II was not IP rated and hence required an external housing for protection from the environment. This double housing can generate problems in extreme environments with heat buildup necessitating incorporation of a cooling fan. In addition the Phase II unit required separate drive/control electronics which were housed within the battery/electronics unit. The Phase III drive system, the Animatics SM34165DT (Figure A-1), has its controller integral to the motor housing which itself is specifically designed to manage the internal heat load under the most arduous conditions.

The salient characteristics for the motor are given below and its performance is highlighted in the torque/power curves provided in Figure A-2:

- Supply voltage: 48-v DC
- No load speed, ~11,000-rpm (The speed is customized to fit tool application, the 11,000-rpm is tailored for 4 ½" metal/stainless cutting disk which is rated at a maximum speed of 13,300-rpm.)
- Continuous motor torque: 12.83-in-lb (205-oz-in)

- Peak torque: 30.00 in-lb (480-oz-in)
- Nominal Continuous power: 615-W
- Peak Power: ~900-W
- Motor weight – 5.5-lb
- Fully autonomous: motor and controller in one unit – no separate control-box

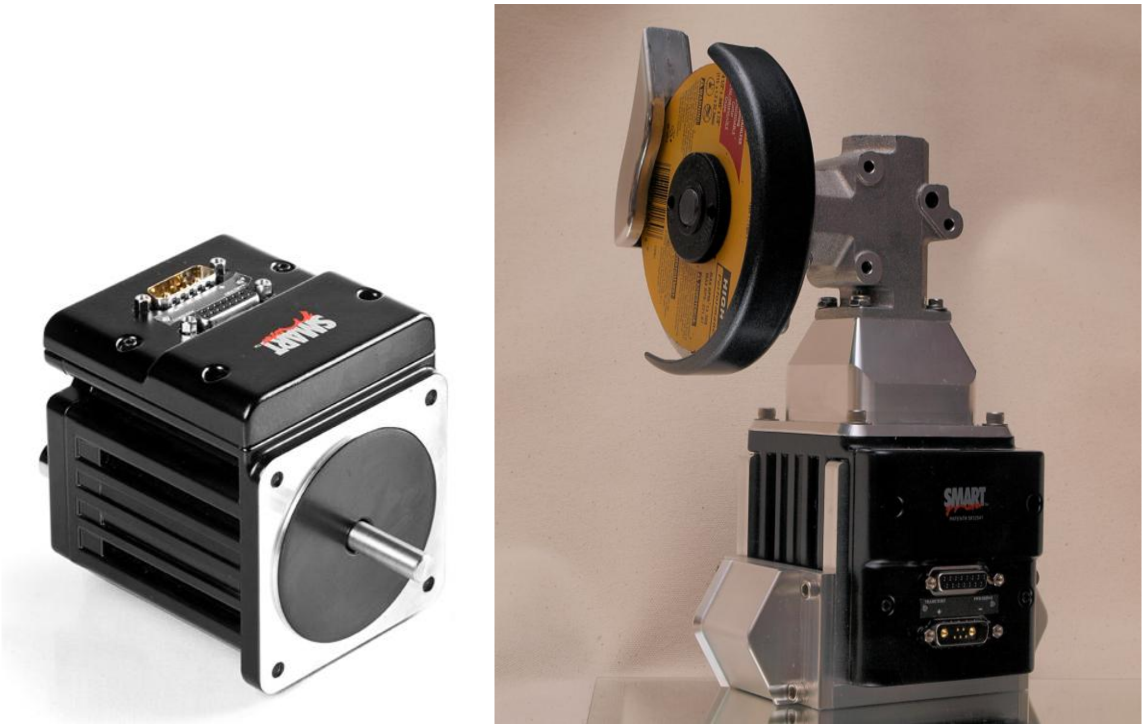


Figure A-1: The Phase III Motor Offers More Power And Integral Controller Electronics In An Environmentally Sealed Housing With Excellent Heat Management Designed In.

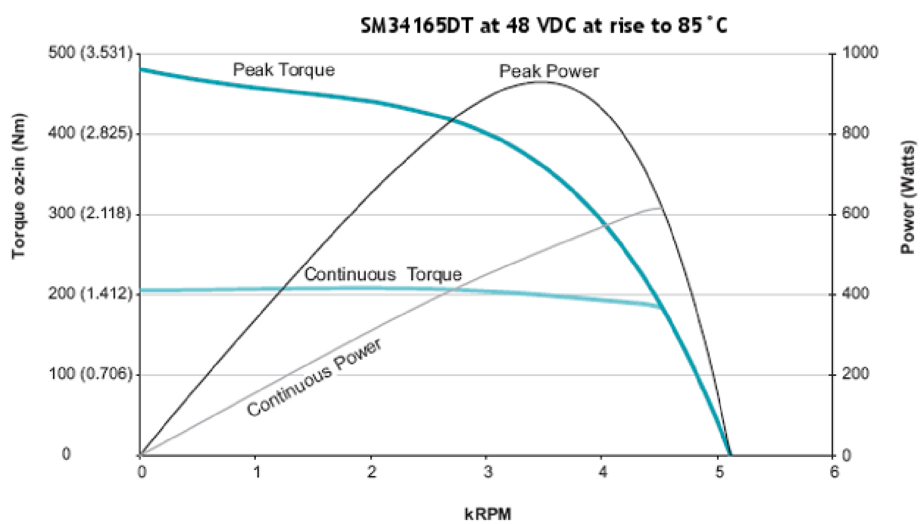


Figure A-2: The New Dervish Motor Has Excellent Torque (Cutting Ability) Throughout Its Power Band.

The new motor selected for the Dervish has significant more power than the earlier units (205-oz-in of torque compared to 80-oz-in) while offering the advantage of being IP-64 rated (sealed against dust and water spray). Figure A-3 shows the new motor configured with the small cutting wheel and held in a vice making easy work of a 1.5-in x 0.125-in steel angle iron. In this Phase III configuration we committed to targeting the larger robot platforms, with their increased manipulator capacity, for the Dervish. This allows us to maximize the performance of the system in terms of cutting without having extreme limitations on tool weight. This current high power Dervish has a tool head weight of 9.5-lb. If the Dervish finds good acceptance in the market and an interest is expressed by users for a unit suitable for smaller platforms it is a simple matter to use a smaller and lighter motor but the user must then accept some reduction in cutting performance.

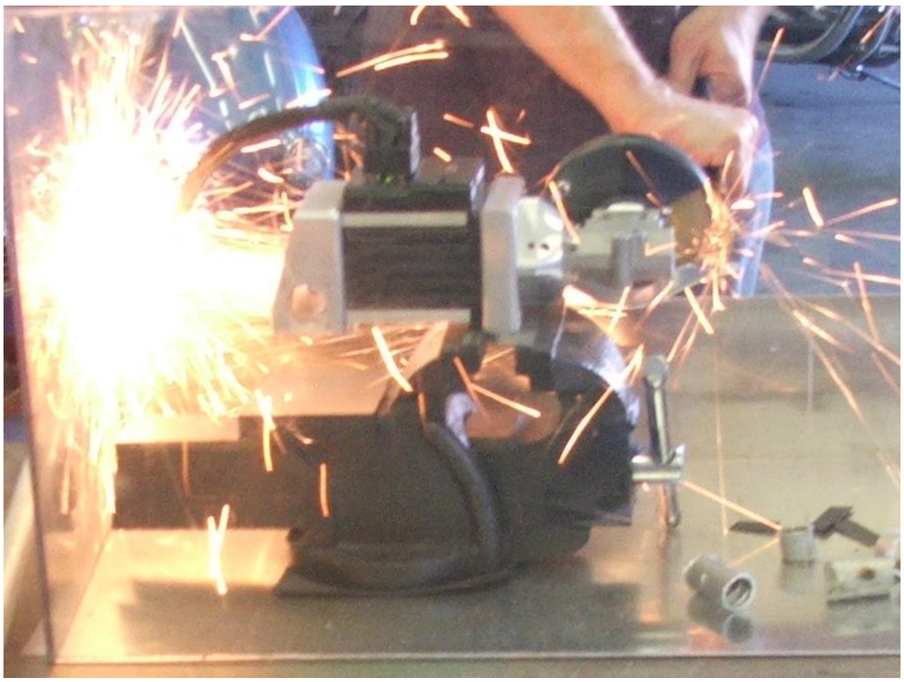


Figure A-3: The New Dervish Motor With Small Cutting Wheel Making Easy Work Of A 1.5-In X 0.125-In Steel Angle Iron.

Another major advantage is that the motor configuration lends itself to adaptation to the various EOD robot platforms via simple add on modules that bolt around the motor and provide ‘hold’ points as applicable to the specific platform and manipulator with which it will be used. Figure A-1 showed the Dervish configured to be held by the Andros manipulator while Figure A-3 shows it set up for the LandShark platform. In addition a “handles” kit would provide the capability for the tool be used as a very capable hand-held cutter/saw/drill. All configurations can be used with any of the tool options (Figure A-4). Shown here is the general purpose cutting wheel used in demonstrations to date but there are a variety of semi-specialized wheels available (Figure A-5) to the operator to optimize system performance to the target.

Figure A-4: Whether Configured For Andros (Left), Landshark (Right) Or Any Other Platform The Dervish Can Be Fitted With All Tool Options.

Figure A-5: A Variety Of Semi-Specialized Cutting Wheels Are Available To Optimize Performance Against The Target – L To R: Thin 4-1/2" Cutting Wheel, Multi-Purpose Circular Saw Blade, Masonry Segmented Diamond Blade, Wet Or Dry Turbo Circular Saw

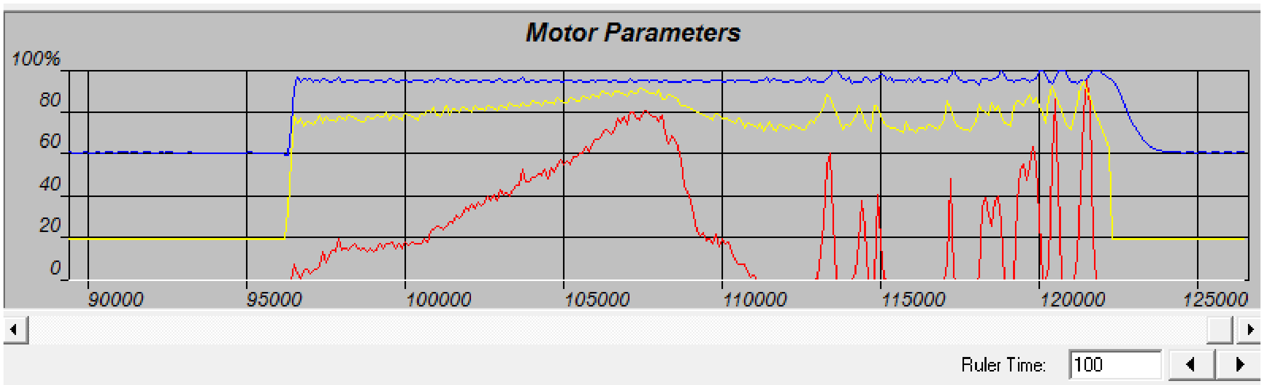
One of the other major advantages that this generation of motor offers over the earlier versions is the sophistication of the controller. The system run parameters can be set up via laptop with different speed, load response etc functions for each tool option (small disk, large disk, reciprocating saw, drill). The operator can then specify which tool is installed via a rotary selector knob on the battery/electronics box. Similarly to the earlier versions then, the controller will manage the system performance but in a tool specific regime:

- cutter idles under no-load conditions, upon power-on
- when load is applied to cutting wheel, the cutter automatically switches to maximum speed/power
- if the load is removed, the cutter returns to idle speed
- if the cutter jams, it will switch to full-power-reverse mode, and then return to full-power-forward
- built-in voltage guard, will turn off cutter before batteries are damaged

With this controller set-up up to 16 pre-programmed options will be available. Currently programs available are:

- Cutting wheels, where the size of the wheel will determine the max RPM of the disk.
  - Programs [cutting wheel speeds] will be available for different type of cutting wheels, depending on cutting wheel size and the type of material cutting to be performed.
  - Using the cutting wheel programs, the unit will idle on power-on; switch to full program-selected RPM range upon detecting a load on the cutting wheel.
  - The unit will strive to maintain full allowable RPM during load, and switch back to idle as load is removed. For safety reasons, these programs allows the cutting wheel to operate *close* [below] to the highest RPM recommended by the wheel manufacturer [wheel diameter dependent], while still providing the fullest amount of torque [cutting power] possible.
  - The unit will detect a jam-situation, where the tool then switches abruptly to full-reverse, to back out of the jam; then switches to full-forward to continue the cutting, all without operator intervention.
  - The unit uses a 2:1, 90° gear assembly.
- Reciprocal saws, the type of saw blade will determine max blade speed.
  - Programs [blade speeds] will be available for different type of reciprocal blades, depending on the type of material cutting to be performed.
  - Using the reciprocal saw programs, the unit will idle on power-on; switch to full program-selected speed upon detecting a load on the reciprocal saw blade.
  - Using a very tight loop control of the motor, the saw blade will maintain its cutting speed – the motor supplies a variable amount of load-dependent torque to make sure that the saw neither bogs down, nor races.
  - The unit uses a 1:1, 90° gear assembly.
- Drill unit, the type of drill bit [and material] will determine max drill speed.
  - Programs [drill speeds] will be available for different type of drill bits, depending on the type of material drilling to be performed.
  - Using the drill unit programs, the unit will idle on power-on; switch to full program-selected speed upon detecting a load on the drill bit.
  - Using a very tight loop control of the motor, the drill bit will maintain its rotational speed – the motor supplies a variable amount of load-dependent torque to make sure that the drill neither bogs down, nor races.
  - Upon detecting a jam-situation, the tool will switch abruptly to full-reverse to release the drill bit from the material; then switch to full-forward operational drill speed to continue the drilling.
  - The unit does not use any gear assembly.

A sample of the “drill bit” program functioning during program development is shown in Figure A-6. Note on the Blue line representing drill speed it is at idle up to about 97,000 [time units]. At that point the drill bit comes into contact with the target and the controller detects a load and switches to “operational speed”. The yellow line represents torque and as the drill switches to operational speed available torque goes up. Red line represents current draw of motor and as the drill switches to operational speed, the current can be seen rising, as the load on the “drill” increases. Note how the torque (yellow line) rises and falls with the load on the “drill”, while the speed (blue line) remains steady, and even during abrupt load/no-load situations neither bog down nor race. Meanwhile, the current (red line) varies abruptly with the load conditions. When load is removed, the drill returns to idle speed.



Parameter	Last	Average	Min.	Max.	Ruler
Current	11	201	0	2878	0
Velocity	227215	273571	-19152	1070630	0
Voltage	23000	23380	22700	227674	23000
AVG CURR	3	43	0	23100	4
TORQUE	6000	10251	3	28520	6000

Figure A-6: Data From A Test Run On Controller Performance Under The Drill Bit Program

Since the control electronics are integral to the motor housing the size of the battery/electronics unit (Figure A-7) has been reduced significantly compared to the Phase II system. This device now merely holds the batteries themselves, their slide-on interface, a main power switch and resettable circuit breaker and a plug for the controller laptop to interface to (used at the 'factory' only). In the final version this box will also hold the tool selector switch to designate which controller regime is to be applied (small disk, large disk, reciprocating saw, drill). The final control to be added to this box will be the control interface – being the on/off switch function handled by the bump switch or Andros interface in Phase II. That control will be configured as a simple switch closure to allow use of any modular device deemed suitable by the operator for initial down-range switching of the Dervish as discussed previously in the Phase II summary (bump switch, whisker switch, proximity switch, direct robot OCU control, etc.). The battery/electronics box is carried on the deck of the robot and in its current configuration with two batteries on board weighs 9.5-lb.

The Phase III Dervish described above addresses all three limitations identified for the Phase II system:

- Complexity. The new design utilizes a COTS motor with integral controller electronics housed in a thermally self- managed IP-64 rated housing and which lends itself to simple integration with modular robot manipulator interfaces.
- Power. The Phase III Dervish easily defeats any reasonable target and the integral smart power controller minimizes power draw while ensuring maximum availability of power and protecting itself against damage occasioned by jams.
- Scalability. Simple motor replacement can significantly reduce system weight (with concomitant reduction in performance) while maintaining all control sophistication.

Figure A-7: The Battery/Electronics Box Has Shrunk Considerable From Phase II And Incorporates The Simplistic Operator Controls.

TPI is currently building several variants of this third generation Dervish for delivery. Our NIJ sponsor will be receiving two units configured for the Andros robot and one for the LandShark platform. RE^2 Robotics, Pittsburgh PA, will be receiving a unit configured for their generic manipulator arm fitted with the family of quick release tools.

Continued development of the Dervish system by TPI with a function of the level of market response.