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A Semi-Autonomous Robot for Stripping Paint from Large Vessels

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Abstract

The National Robotics Engineering Consortium and UltraStrip Systems Inc. have developed a highly flexible and productive robot to strip paint from large ships and other large ferro-magnetic structures based on the patents obtained by UltraStrip Systems, Inc. (US patents: 6,425,340; 5,849,099; 5,628,271). Removal of corrosion and coatings from large vessels has become a serious economic and environmental problem, and current practices are becoming infeasible. The M2000 robot removes paint from ships using ultrahigh pressure water jets and recovers the water and debris in an environmentally sound way. The addition of simple, easy-to-use, cruise control features to the robot has permitted significant increases in productivity, safety, and stripping quality.

KEY WORDS—autonomy, robotics, water jetting, paint stripping, coatings removal, ship maintenance

1. Motivation

1.1. Problem

Stripping coatings and corrosion from large ships has become a serious problem. Consider that a typical super tanker has over 30,000 m^2 of exterior hull surface that must be stripped or swept (a partial stripping of loose coatings) at least once every five years. Hulls can be in excess of 30 m tall and include a variety of surface obstacles, high-profile welds and complex curved regions. While stripping the near-vertical sides and curved bow and stern areas of a ship presents one set of challenges, the industry desire is for a system that can also strip the bottom of the hull. When in drydock, ships are placed on hundreds of blocks, which must be navigated around to access the bottom area. Drydocking large ships is very expensive, both in drydock fees, and in downtime for the vessel, so coating removal must be accomplished quickly. To complicate matters, the coatings being removed typically contain hazardous chemicals (such as the fungicide tri-butyl-tin) designed to retard marine growth. In most industrialized countries, stripping waste must be handled according to strict environmental regulations.

1.2. Current Practice

The majority of large vessels today are stripped using traditional grit-blasting techniques. Multiple sandblasting units powered by compressed air are used to strip away coatings and corrosion. This technique requires relatively simple equipment and unskilled operators. Although grit blasting produces a satisfactory result, it has a number of major drawbacks. The first problem is that grit blasting is labor intensive. An average worker can strip about 6 m^2 per hour (da Maia 2000). This translates to over 5,000 man-hours to strip a typical super tanker. To strip a ship in reasonable time, a shipyard will often employ over 100 men per shift, 24 hours per day. Since this work is only occasionally needed, and since it is extremely tedious, dangerous, and unpleasant, filling work crews this large can be a challenge.

Grit blasting methods also have a number of operational drawbacks. The large amount of airborne grit generated during blasting precludes most other work on the ship, and can require significant cleanup on decks and in critical machinery areas. The blasting method also requires complete scaffolding and tenting (in some countries) of the vessel. Setting up and tearing down this infrastructure further prolongs the stripping operation and adds to the cost. Additionally, the grit blasting process can drive salts and other debris into the micro-textured surface of the steel hull, compromising paint adhesion (da Maia 2000).

Grit blasting methods also create several severe environmental problems. First among these is that the blasting turns

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Fig. 1. Grit-blast crew at work.

toxic hull coatings into a fine, airborne dust. Despite tenting procedures, a great deal of this toxic dust still ends up in workers' lungs, in surrounding communities, and in bays, rivers, and oceans. The second problem is disposal of the thousands of tons of grit that is contaminated with paint residue. Stripping a large ship generates in excess of 3000 tons of grit. In many locales, disposal of the grit is a serious environmental and cost issue.

High labor costs and environmental complications associated with grit blasting have driven much of the coating removal business to countries with lax environmental laws. In some of these countries, used toxic grit is dumped in the ocean, with terrible consequences for marine ecosystems. At the same time, countries with sound environmental policies lose both the stripping work as well as the other high value maintenance jobs, which are usually performed during the same drydock visit.

To address concerns with grit-based methods, some shipyards are now turning to ultrahigh-pressure (UHP) water jetting or "hydro blasting". The US Navy requires hydro blasting on all surface preparation jobs for quality, minimal cleanup and environmental reasons. Cruise line operators are also beginning to demand hydro blasting due to its very positive environmental benefits. The UHP process uses water jets with a pressure of 2500 bar or greater to remove coatings from the ship hull. This technique has a number of advantages over grit blasting, the greatest of which is the elimination of the grit and its associated pollution and surface contamination problems. Unfortunately, hand-held UHP guns are cumbersome and fatiguing to operate and typically are less productive than grit blasting (da Maia 2000; Riu 2000). Wastewater recovery can also be an issue with hand-held guns, and UHP equipment is expensive compared to grit blasting equipment (Riu 2000).

To make the most of the UHP process, and to overcome the problems with hand-held UHP guns, many companies have developed simple machines to carry one or more UHP nozzles across the hull of a ship. These machines typically include a shroud, which encloses the stripping process, and a vacuum system to recover wastewater. To date, at least seven machines are available from companies in the US and Europe (Goldie 2000). These machines fall into two classes. The first class is a boom- or arm-mounted stripping head, which is moved across the surface by a mobile base on the drydock floor. One example of this type is the Hammelmann Dockmaster, a small boom truck which drives back and forth in the drydock to maneuver the stripping head across the surface of the ship (Hammelmann 2002). While these machines are theoretically capable of high production rates, they rely on correct positioning of the mobile base and boom to hold the stripping head at a proper spacing and orientation to the ship surface. The many complex curves on typical ships make this a challenging problem and operators of these machines have reported that control is awkward and frustrating. Boom-type machines also require an unobstructed area beside the ship in drydocks, which is often unavailable due to ever-increasing ship size and the multitude of other operations occurring in the drydock area. For these reasons, only a few mobile base type machines are in use.

The second and more common type of UHP stripping machine is the vacuum-attached crawler. These machines typically use a single vacuum system for wastewater recovery and for attachment to the ship hull (see Figure 2). The machine is driven across the hull by wheels or tracks, which are electrically or air powered. Most of these units rely upon a winch system to provide fall protection and to help pull the machine over difficult spots. The most popular unit in this class is the Flow Hydrocat (Flow 2002). Similar machines are produced by several other companies.

These vacuum-attached crawlers typically carry a high-flow UHP system capable of many times the stripping rate of a man with a UHP gun. The stripping process is entirely enclosed, which eliminates pollution, dust, and the need for tenting. The vacuum shroud reduces noise (UHP guns and grit blasting are both very loud) and allows non-stripping work to be performed concurrently with the stripping process. The vacuum-attached robot requires no scaffolding and needs minimal space to operate.

Vacuum-attached robots and another variant, magnetic-tracked crawlers, have seen only limited application in shipyards. Only about 100 are in occasional use worldwide. In discussions with several industry experts from shipyards, coatings companies and stripping contractors, it seems that the reason for this is that the machines have failed to live up to performance expectations and have a high cost per square meter stripped.

Fig. 2. Commercial vacuum-attached machine.

At the National Robotics Engineering Consortium (NREC), we tested three of the commercial stripping machines. The machines were tasked with stripping typical epoxy-based ship coatings from an approximately 200 m^2 steel test wall, which includes convex and concave curves, and vertical and horizontal (upside down) surfaces similar to those found on typical large ships. In all cases, the machines were driven by experienced professional operators. The machines were timed and video taped while stripping a variety of pre-measured areas. This allowed us to compute throughput in terms of square meters stripped per hour.

In our tests, the machines were connected to UHP pumps capable of delivering enough water to operate several handheld guns. In each case, however, the machines turned in poor productivity numbers. While several factors appeared to contribute to this poor performance, the most significant issue seemed to us to lie with the attachment concept. The first two machines, which used the vacuum within the cleaning shroud as their primary means of attachment to the hull, were speed limited and frequently broke contact with the test wall. The force provided by the vacuum attachment must be strong enough to hold the machine in position on a vertical surface and provide the normal force required for locomotive traction, but cannot be too strong or the robot literally becomes stuck in place. In practice, the robots would usually have too little vacuum force, in which case they would fall off (which happened often), or too much, in which case they would be difficult to drive. Progress was often slow, jerky, and awkward, and poor controllability often led to the need to reverse to re-strip a missed area. Both vacuum-attached robots had trouble with significant surface variations (such as weld seams) which would break the vacuum seal and cause a fall. Operating in any mode other than stripping vertical swaths of paint was difficult and it was impossible to move at the high speeds required for efficient sweeping operations.

The third robot, produced by JetEdge, Inc., was a magnetic-tracked UHP crawler (JetEdge 2002). Owing to its rigid tracks, this machine was unable to handle curved areas and significant obstacles. The tracks also heavily marked the underlying paint layers during turning and heading correction, which is problematic during sweeping operations where the lower paint layers are to be preserved.

We believe that the primary barrier to widespread acceptance of the water-based stripping of ships lies not in the UHP process, but in the poor performance of the commercially available robotic systems. A fast, agile, and easy to control robot would be much more productive than anything developed to date and would enable the use of robotic systems for high-speed sweeping jobs as well as for "spotting" jobs, which require a machine to move quickly from one area to another in order to strip only the failed spots in the coating.

2. The M2000 Robot

The NREC was approached in 1999 by UltraStrip Systems to assist in their development of an automated robot appropriate for high production stripping and sweeping of ship hulls and storage tanks. Together, we have developed an automated machine that addresses many of the problems with current techniques. Multiple copies of the latest version of the robot are now in use in several shipyards and oil tank farms and have stripped more than 30,000 m^2 of paint during a six-month period spanning 2001 and 2002.

The robot uses UHP water (3000 bar) to strip coatings and corrosion, and a vacuum to recover virtually all of the debris stripped from the vessel. Since the process is entirely enclosed, the problems associated with pollution, grit contamination of machinery, waste disposal, and health hazards are eliminated. Moreover, the robot is many times faster than a human blaster and the need for scaffolding and tenting is removed, which saves time and allows maintenance work on other parts of the vessel to progress concurrently with stripping. These features allow ships to be repaired and returned to service more quickly.

To date, we have built three versions of the paint removal robot (see Figure 3). Although they stripped paint well, the first two machines were somewhat large, cumbersome, and relied on magnetic wheels for attachment to the ship. The third robot (dubbed "M2000") was designed to improve agility and overall productivity. In the following section, we describe the design and construction of the M2000.

Fig. 3. The three versions of the NREC-UltraStrip Systems robot chronologically from left to right. The wires in the right-hand image are passive inertial safety reels to catch the robot in the event of a fall.

2.1. Design Philosophy

Our primary goal in the design of the M2000 was to create a machine that would allow users to realize the full benefits of the UHP stripping process. This meant a machine that would be confident, fast, and maneuverable on all areas of a ship's hull and which would be tough enough in the shipyard environment to work reliably day in and day out.

The shipyard environment, at which the M2000 is targeted, is an extremely challenging one. The drydock is a rough and dirty place filled with corrosive salts, barnacles, and a wealth of ship-borne and industrial debris. Work in the drydock involves heavy machinery, airborne spraying of paints and other chemicals, and endless welding, cutting and grinding operations on hulls and ship structures. Workers in the shipyard vary widely in technical skill and attitude towards automated machinery. The work moves forward at a hectic pace and under tight schedules. Managers typically have well-founded skepticism towards high-tech machines that cannot stand up to regular shipyard abuse.

With this environment in mind, the M2000 has been designed to be as tough as possible. The major structures in the machine were designed using finite element analysis to withstand worst-case loads while remaining lightweight. Failure points were analyzed and intentionally designed to occur in low-cost, easily replaced components. Corrosion-resistant materials such as titanium, stainless steel and various plastics were used wherever possible. Motors, sensors, and electrical connectors are fully sealed so that the entire robot can be hosed down or even briefly submerged without concern. The M2000 was designed for simplified use and maintenance. The major components are connected using large, quick-release pins or over-sized fasteners, which can be removed with common tools. Regular required maintenance is minimal. Continuous testing programs and field trials were used to provide design feedback and improve toughness.

2.2. Water Jetting System

The heart of the paint-stripping robot is the UHP water jetting system. Since water jetting has been in use for coating removal for years, all of the UHP system components are commercially available.

The current version of the robot operates at 3000 bar, moving a total of 37 l min^{-1} through spray jets. Water is delivered via a 76 m high-pressure hose that is part of the robot's tether. Although the volume of water is relatively small, the power behind the jets is significant. Power for the UHP water comes from a 325 hp turbo-diesel and is concentrated on jets with a total area of just 1.1 mm^2. No abrasive is added to the water, but the jets are still powerful enough to bore holes in steel if left in one spot for several minutes.

Since the water jets are able to blast away coatings and corrosion on contact, they can be moved very quickly to maximize the productivity of the robot. The current robot mounts its jets on a spinning head with four spray bars. At 2000 RPM, the outer jets achieve a linear speed of 143 km h^{-1}.

2.3. Vacuum and Filtration System

The UHP spray head is carried in a vacuum shroud that completely encloses the stripping process. A polyurethane

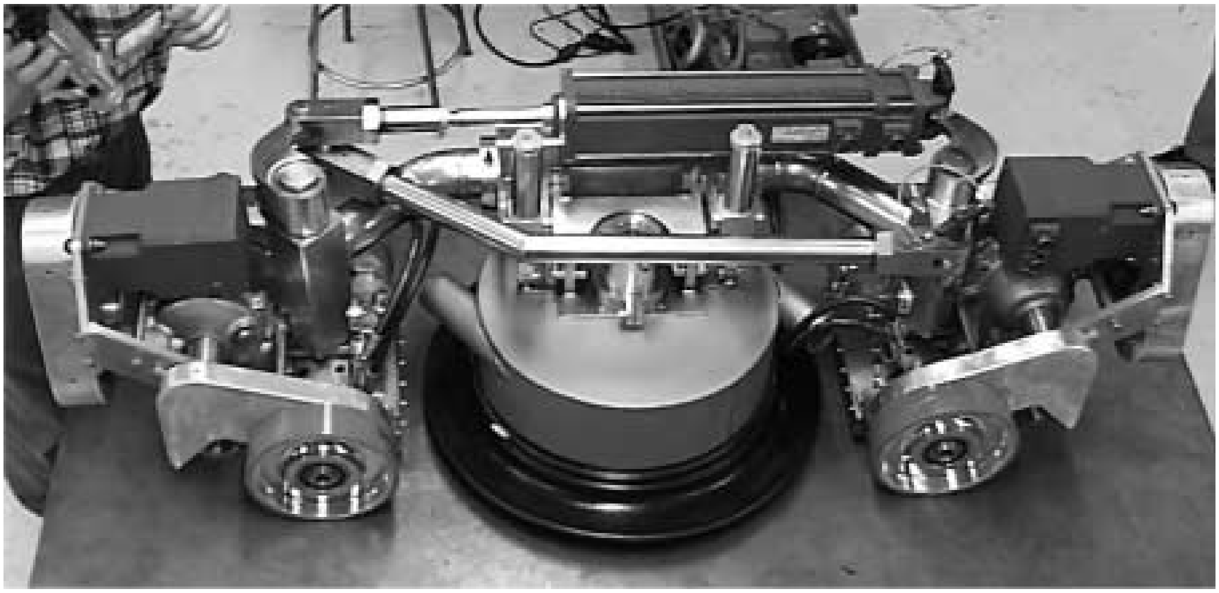


Fig. 4. Overview of M2000 robot.

seal surrounds the head, helps conform to the surface to be stripped, and provides an inlet pathway for vacuum air. Removal of a single pin allows the entire head to rotate up for quick service of the spray head and vacuum seal.

Water and stripped debris are carried away from the heads by an industrial vacuum system. For the current robot, we use a 56 kW vacuum, which pulls approximately 128 m^3 per minute through the shroud with a vacuum of about 38 cm Hg.

The output of the stripping process is drawn through a 100 m hose into a holding tank, and then pumped through a particle separation system to remove the majority of the solid waste. This waste is ejected from the separator as a dry powder. Any dissolved contaminants are then removed from the water by a sand filter and a secondary filter tailored to the chemicals expected in the waste (for example, tri-butyl-tin). The resulting wastewater is clear to the eye, and meets typical standards for disposal in a sewer or directly into rivers and oceans.

2.4. Magnetic Attachment

The M2000 robot uses permanent magnets to provide the force required to hold the robot on the ship. When the robot is upside-down, the magnets must sustain the entire 216 kg weight of the machine. In practice, however, the holding force is not the driving factor for magnet size.

When driving on vertical surfaces, the magnets must provide sufficient normal force to develop the traction to pull the robot plus the weight of cables and hoses, up the side of a ship. Weld beads or other obstructions increase required tractive effort. Since smooth paint, water and oily residues result in low coefficients of friction, this normal force usually needs to be substantial. On the M2000, the magnets provide six times the worst-case holding requirement, which provides enough normal force to develop good traction on all but the most slippery surfaces.

Fig. 5. Vacuum shroud with 10-jet spray bar configuration.

Two large magnets are mounted beneath the front and rear axles of the machine. The robot is designed to accommodate

Fig. 6. M2000 stripping a storage tank.

paint thicknesses up to 6.3 mm, which create a large gap between the magnet and steel, thereby significantly reducing the magnetic force holding the robot in place. The large normal force provided by the magnets allows the robot to drive confidently on smooth, wet, and even oily surfaces while supporting its long and heavy tether.

2.5. Steering and Suspension

The robot is intended to access the majority of the hull surface of a large ship. This means that it needs to be capable of traversing both convex and concave curves with radii as small as 2 m. The machine also needs to be able to operate in tight areas and around obstacles such as portholes and hatches as well as around the blocking which supports the ship in drydock.

To provide the required maneuverability, the machine is designed with four-wheel steering. For strength and simplicity, the machine uses solid half-axles which counter-rotate to steer like an airport baggage cart. While this allows very tight turning, it also requires the use of differentials to prevent skidding of the wheels during turns. The two small differentials have a limited slip capability to provide true four-wheel drive across a variety of surface conditions. To ensure that all four wheels remain in contact with the surface, even in highly curved areas of the hull, one of the two axles is designed to “float”. This gives the machine a simple but effective suspension similar to that used on most farm tractors.

Fig. 7. M2000 stripping stern of a cargo ship.

The cleaning head is designed to ride on the surface independently of the robot frame and wheels. To accomplish this, the head is mounted on a four-bar mechanism equipped with adjustable air cylinders which force the head against the hull of the ship.

2.6. Actuation

The robot needs to be capable of traversing various obstacles such as welds, flanges, and uneven plate joints on the ship’s hull. The high normal force of the magnets means that the effective load on the wheels of the robot can be extremely high for the small wheel diameter. This, and the need to lift heavy hoses and cables as high as 40 m up the side of a ship, requires a great deal of torque at the wheels. To overcome this problem the robot uses a pair of large, high-performance electric motors with built-in planetary gear heads, encoders and brakes. Electric drive was chosen because it is cleaner than hydraulics, which might leave oil on the freshly stripped surface, and because it provides better control than air drives. Final reduction is provided by two stages of external chain-driven gears. The reduction achieved in this way gives the robot a drawbar pull of over 5300 N and provides ample torque for lifting heavy tether loads over the obstacles typically encountered on ship hulls.

We wanted a robot that could steer almost as quickly as an operator could move the joystick. Axle steer loads are high due to the high normal loads on the wheels and the limited-slip differential parasitic torque. Steering loads increase considerably when one wheel is crossing an obstacle while steering. A 5300 N self-contained electric steering actuator is connected to a linkage which provides simultaneous steering of the two axles and has proven to be a key part of achieving highly agile performance. The key to the actuator's high force and high-speed capability (0.25 m s^{-1}) is its unique planetary roller screw design and integral motor.

The configuration of the robot and choice of actuators has proven to work well. Under almost all conditions, the robot is capable of driving quickly and confidently at any angle and at relatively high speeds (35 m min^{-1}).

3. Basic Automation Features

The robot is operated using an industrial-style radio control unit, which allows it to be driven like a toy radio-controlled car. The signals from the radio unit are routed through an embedded micro controller which converts the joystick and button inputs from the control unit into appropriate signals for the robot actuators and air valves. This fly-by-wire style control scheme has proven to be very effective since it allows the software to “massage” the operator input to implement gains, offsets and limits for the various control signals, and to implement a variety of simple behaviors for safety and convenience. Since this is all done in software, the low-level behaviors of the robot can be changed and tested quickly.

Several low-level behaviors which simplify operation of the robot have been implemented using the micro controller. Safety features implemented in this way include automatic E-stop on any hardware or software fault, and automatic shutdown of the UHP jets when the robot is stopped. Other conveniences available to the operator include two levels of speed-based cruise control with fine adjustment, a steering trim control to keep the robot driving straight independent of surface curvature, and automatic raising and lowering of the stripping head.

The result is a robot which is intuitively simple to drive, which accelerates and turns smoothly and quickly, and which gives the operator a precise and predictable feel for the control of the machine. These built-in safety and control features have proven to be useful and effective in the shipyard.

4. Advanced Automation Features

The M2000 drives over 5 km during a busy working day. This is exacting and tedious work since the robot must be continuously driven to closely follow the previous stripping swath and then quickly repositioned at the end of each cut. Wandering off the path just a little will leave an unacceptable band of missed coating, while overlapping the previous swath by too much wastes stripping capability.

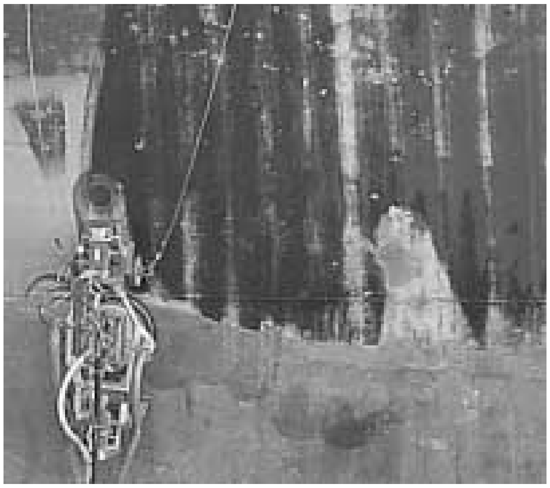


Fig. 8. Mottled surface after sweeping.

During extensive testing and operation of these robots, it became clear that an obstacle to productivity is the human operator. Operators can only concentrate effectively for 30–60 min before their performance in driving degrades and the productivity of the robot suffers. To address this, we have developed and tested (but not yet deployed commercially) several features which help to automate the driving of the robot. The goal of these features is not to remove the human from the loop, but to make the driver more efficient and productive.

4.1. Cut-Line Tracking Cruise Control

Due to limitations on hose and cable lengths, stripping of a ship is normally performed in sections 75–100 m wide. Within a section, the hull is typically stripped in vertical swaths 35 cm wide. Each successive swath overlaps the previous one to ensure complete removal of the coating. This is similar to the process of mowing a grass lawn. The maintenance of a reasonable, consistent overlap makes the job difficult for the human operator.

The cut-line tracker is a computer-vision-based capability which automatically steers the robot along the paint/steel boundary while maintaining a precise overlap. To use this feature, the operator manually cuts the first strip of paint, which can be straight or curved to follow the contours of the hull. From then on, the robot will automatically cut successive strips by following the cut-line created by the previous pass.

This feature frees the operator from the difficult and tedious task of maintaining the optimum overlap. Since the robot is much better at this than a human operator, less of the robot's cutting capacity is wasted through excess overlap or in having to reverse to pick up a missed strip of paint.

Fig. 9. Processed tracking image with clean, wet steel on the left.

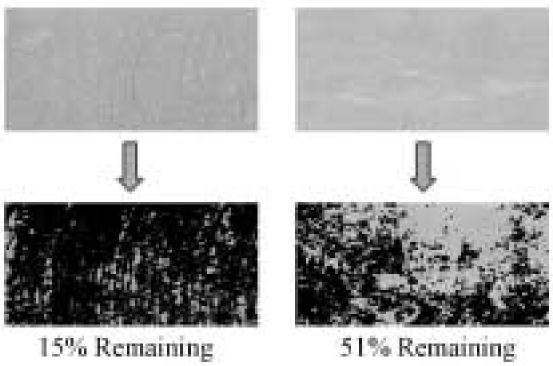


Fig. 10. Results of paint detection.

The cut-line tracker uses a computer vision algorithm which relies on a color histogram-based correlation to find likely line points, and an aggressive line fitting algorithm to fit the most likely cut line.

The image in Figure 9 shows the view from the forward-looking robot camera after undergoing computer processing to find the cut-line. The dots indicate the estimated location of the cut on each scan-line, while the vertical line indicates the recovered cut line which is used by the computer to steer the robot.

Notice that the cut-line tracking succeeds despite paint variations, steam, wet patches on the steel, and glare from the painted surface.

4.2. Paint Residue Cruise Control

The cut-line tracking cruise control will steer the robot, but it still requires the operator to set a preferred driving speed and to adjust the driving speed as necessary to accommodate changes in hull and coating conditions. Slower driving speeds remove more paint, while faster speeds remove less paint.

Since coating conditions vary greatly from one part of a ship hull to another, controlling the robot speed is important to getting the best quality strip and to getting the best performance out of the robot. The paint residue cruise control monitors the quality of the stripping process behind the robot and adjusts the robot's speed to produce the desired quality of stripping result.

A knob on the remote control box allows the operator to preset the degree of stripping desired. From then on, if the hull is insufficiently stripped, this program automatically slows the robot down. If the hull is well stripped, the program automatically increases speed to maximize productivity.

This "paint residue detector" works by detecting clean steel in the camera view. The program has been trained from a set of sample images to recognize the statistical color characteristics of steel. It uses this knowledge to automatically compute the percentage of paint remaining on the hull surface after stripping. This number is used to control robot speed and can be logged to produce statistics on the quality of the stripping job.

Figure 10 shows the results of the paint residue detection processing. The top two images show views from the rearward-looking camera on the robot before processing. The bottom images show only the paint detected in the images. Clean steel in each image has been converted to black.

To date, the paint residue cruise control has worked well in testing. Choosing the best set of "typical steel" training images and contending with reflections and extreme lighting variations are problems that still need to be solved in future research.

5. Testing and Deployment

The three versions of the robot were extensively tested over the two-year course of development. This testing included week-long runs of 24 hours per day using inexperienced operators under real-world conditions. During this time, hundreds of kilometers and hundreds of hours were put on the machines in order to expose weaknesses and refine the design for application in the challenging shipyard environment.

The third version of the M2000 was also tested in a head-to-head competition with one of the commercially available,

Table 1. Results of Competitive Trials

Test	Time to Complete		M2000 Advantage
	M2000	Vacuum Attach	
$9m^2$ Full Strip	9.6 min	26.4 min	2.75x
$1.9m^2$ Sweep	11.2 sec	60 sec	5.4x
15.7m Spotting Job	27 sec	114 sec	4.2x

Fig. 11. Clockwise from top left: under-hull operation; sweeping the bow; dockyard with pump and vacuum containers; stripping failed coating.

vacuum-attached machines. We ran both machines on our test wall and challenged them to perform several typical stripping, sweeping and spotting tasks. In this competition, the M2000 was consistently faster than the vacuum-attached machine and was a great deal faster sweeping and spotting—tasks which require speed and agility. Due to the smoother operation and more accurate control, the M2000's sweeping results were also considerably better than the vacuum-attached machine which heavily scored the steel as it started and stopped.

The first deployment of the M2000 to a shipyard took place in August 2001, approximately two years after the start of development at the NREC. The shipyard environment was as difficult as could be imagined but the robot survived a fall from the side of the ship (due to driving over cables in poor lighting) and numerous obstacles.

Further testing took place using two robots to strip, sweep and spot seven additional large vessels and another robot stripping barge decks and above ground storage tanks. Table 2 shows the results of these first eight major stripping jobs. Over the course of 41 days, two machines drove over 80 km and stripped, swept and spotted over 30,000 m^2 of hull.

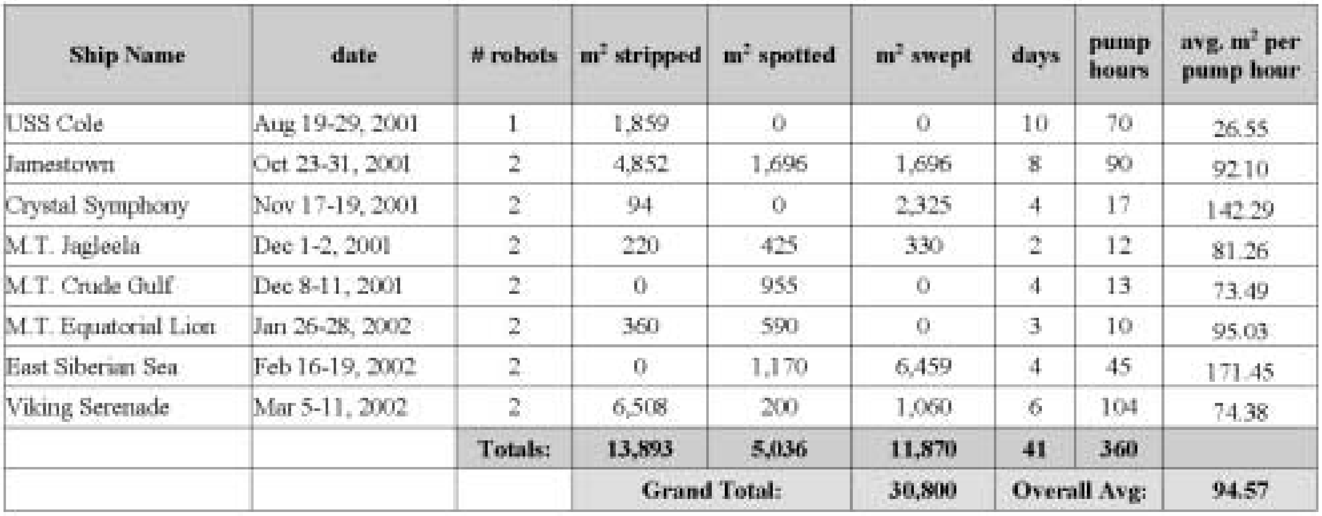
Overall, the initial record compiled by the machines is encouraging. At an average of 94 m^2 per pump hour, this rate is roughly ten times the rate of a man using an UHP gun (da Maia 2000). Moreover, significant effort was saved by doing away with the tenting, scaffolding, and grit cleanup phases of a typical stripping project. A further benefit came from reduced environmental impact and decreased waste disposal costs.

6. Lessons Learned

During the course of this project, we did a few things right and, of course, made some mistakes. Some of the key elements that contributed to a successful outcome are described below:

Realistic Test Facility. A considerable amount of effort was spent building a large (30 × 10 m^2) steel wall on which to test and validate the machine. The wall was later extended

Table 2. M2000 Shipyard Operations



Ship Name	date	# robots	m^2 stripped	m^2 spotted	m^2 swept	days	pump hours	avg. m^2 per pump hour
USS Cole	Aug 19-29, 2001	1	1,859	0	0	10	70	26.55
Jamestown	Oct 23-31, 2001	2	4,852	1,696	1,696	8	90	92.10
Crystal Symphony	Nov 17-19, 2001	2	94	0	2,325	4	17	142.29
M.T. Jagleela	Dec 1-2, 2001	2	220	425	330	2	12	81.26
M.T. Crude Gulf	Dec 8-11, 2001	2	0	955	0	4	13	73.49
M.T. Equatorial Lion	Jan 26-28, 2002	2	360	590	0	3	10	95.03
East Siberian Sea	Feb 16-19, 2002	2	0	1,170	6,459	4	45	171.45
Viking Serenade	Mar 5-11, 2002	2	6,508	200	1,060	6	104	74.38
		Totals:	**13,893**	**5,036**	**11,870**	**41**	**360**	
			Grand Total:		**30,800**	**Overall Avg:**		**94.57**

to provide sharp curves and inverted areas to simulate a ship hull. The wall was stripped and repainted with epoxy ship coatings countless times. While this mockup was expensive, it was well worth it because it permitted extensive and realistic testing of the machine before visiting a shipyard.

Close Contacts with Industry. During the course of development, we maintained close contacts with the industry. Our industrial partner, UltraStrip Systems Inc., worked hard to develop contacts with shipyards, coatings manufacturers, ship owners and government representatives. These people were invited to periodic open house events at which they could see our progress and provide critical feedback. These contacts also gave us access to shipyards, which we visited to learn more about the environment and current practices.

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