Preliminary Concept Trial of the
Semi-Automated Paint Containment System

Richard J. Norcross

Intelligent Systems Division
National Institute of Standards and Technology
Technology Administration
U.S. Department of Commerce
Gaithersburg, Maryland 20899

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Abstract

The Carderock Division of the Naval Surface Warfare Center (NSWC-CD) is developing the Automated Paint Application, Containment, and Treatment System (APACTS) to apply anti-corrosive and anti-fouling paints in an environmentally sound manner. NSWC-CD commissioned the Intelligent Systems Division of the National Institute of Standards and Technology (NIST) to construct a concept prototype of a Semi-Automated Paint Containment System (SAPACS). SAPACS utilizes a portion of the APACTS technologies to provide an intermediary system that can reduce shipyard hazardous material emissions with less capital investment. NIST assembled SAPACS from an existing Coordinated Aerial Work Platform (CAWP) and an existing lift capable environmental tank (E-Tank). NIST modified the E-Tank to detect the ship's hull, to generate pitch motion, and to command the CAWP in accordance with conventional hierarchical control. SAPACS is able to move along the ship hull with operator supervision but without operator direction. This leaves the operator free to perform the painting tasks while the SAPACS moves. Atlantic Marine Dry Dock Company tested the SAPACS prototype at their Jacksonville yard in November of 2002 and found the system to be welcomed by the shipyard painters.

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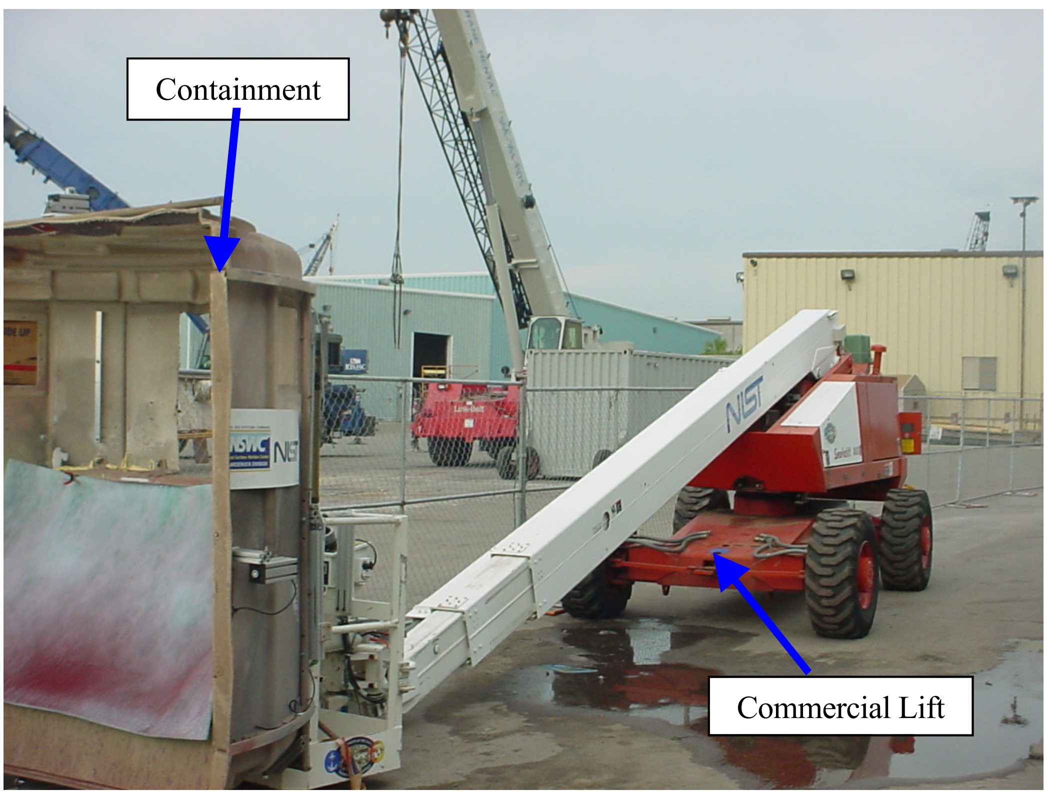
1 Summary

The Carderock Division of the Naval Surface Warfare Center (NSWC-CD) is developing the Automated Paint Application, Containment, and Treatment System (APACTS) to apply anti-corrosive and anti-fouling paints in an environmentally sound manner. NSWC-CD commissioned the Intelligent Systems Division of the National Institute of Standards and Technology (NIST) to construct a concept prototype of a Semi-Automated Paint Containment System (SAPACS) (Figure 1). SAPACS utilizes a portion of the APACTS technologies to provide an intermediary system that can reduce shipyard hazardous material emissions with less capital investment. NIST assembled SAPACS from an existing Coordinated Aerial Work Platform (CAWP) and an existing lift capable environmental tank (E-Tank). NIST modified the E-Tank to detect the ship's hull, to generate pitch motion, and to command the CAWP in accordance with conventional hierarchical control. SAPACS moves along the ship hull with operator supervision but without operator direction leaving the operator free to perform the painting tasks. Atlantic Marine Dry Dock Company tested the SAPACS prototype at their Jacksonville yard in November of 2002 and found the system to be acceptable to shipyard personnel and a benefit to productivity.

Figure 1 SAPACS



APACTS has four major component systems: paint delivery, overspray containment, overspray treatment, and manipulation. The manipulation system moves the paint and containment systems along the hull at the end of a high-speed micromanipulator that is carried across the hull by a large-volume, low speed macro-manipulator. The mico-manipulator is, in turn, carried about the dry dock by a motorized base. SAPACS uses the motorized base and macro-manipulator portions of the APACTS manipulation system.

The SAPACS macro-manipulator is a modified aerial work platform. Each actuator has a position sensor and a servo controller. A coordinating computer directs the servo controllers to move the actuators. While a typical commercial aerial work platform moves along and about the axis of its individual joints, motion coordination permits the modified work platform (a.k.a. a Coordinated Aerial Work Platform or CAWP) to move in intuitive directions such as up, down, left, right, and along a ship's hull.

SAPACS does not use the APACTS paint delivery, treatment, or containment systems. With SAPACS the painter paints and there is no treatment. SAPACS captures paint overspray with a modified environmental tank (E-tank). The E-tank includes a pneumatically driven fan that draws air from around the E-tank and through a paint filter. When the E-Tank is close to, and aligned with the hull the airflow prevents the overspray from escaping into the surrounding environment.

For this test, researchers added a motor, a controller, and various sensors to a Spider E-Tank from Flow International. The motor gives the E-tank a pitch motion (rotation about the horizontal). The sensors monitor the tank's pitch and the position and orientation of the hull in front of the tank. The controller reads the sensors, commands the pitch motor, and directs the motion of the CAWP to move along the hull and maintain a suitable distance from the hull.

Atlantic Dry Dock Corporation tested the SAPACS at their Jacksonville, FL yard in November 2002. The yard personnel quickly appreciated the potential for SAPACS to improve their work environment and continued to use the prototype after the official test. Atlantic Dry Dock was unable to conduct a full time and motion study. However preliminary conclusions can be derived from prior experience, informal observations, and programming parameters.

The ultimate goal for SAPACS is to provide overspray capture without reducing the painter's productivity. The SAPACS concept prototype afforded less productivity than the uncontained painter. However the prototype, with coordinated motion of the aerial work platform, provided a production rate that was 60% greater than the painter using the environmental tank without coordinated motion. Furthermore, once SAPACS is enhanced to follow the surface at 7.6 cm/s (3 in/s), SAPACS can restore the painter's productivity while capturing the paint overspray.

2 Introduction

To guard against the harshness of the sea, ship hulls are covered with various paints that must be periodically replaced to maintain their effectiveness. During paint application a portion of the paint spray, called the overspray, flows past the surface and falls onto the drydock and surrounding areas. The overspray may contain contaminants such as: heavy metals (e.g., copper and zinc), hazardous air pollutants (HAPs), and volatile organic compounds (VOCs). The airborne overspray exposes shipyard personnel to undesirable and unacceptable risks, while the heavy metal particles deposited in the drydock subsequently migrate to the harbor causing severe and widespread environmental damage.

The Carderock Division, Naval Surface Warfare Center, (NSWC-CD) conducts research and development leading to fleet implementation of materials, processes, and equipment that enable Navy ships and shipyards to better fulfill the Navy's missions. The Pollution Prevention and Material Safety Branch (Code 632) provides the Navy with the technical expertise to solve existing and emerging waste management problems to ensure that the Navy is environmentally responsible. The Paints and Processes Branch (Code 641) advances coating and preservation technologies that result in increased performance of Navy coatings and improved material readiness and overall operational performance of Navy ships. Pursuant to these responsibilities, NSWC-CD is developing the Automated Paint Application, Containment, and Treatment System (APACTS) to apply advanced coatings, to improve paint application, and to significantly reduce particulate discharge from the painting of ships.

The Intelligent Systems Division of the National Institute of Standards and Technology (NIST-ISD) supports APACTS development through investigation of new and existing technologies to carry, maneuver, and manipulate the APACTS sprayer and containment system. Since a single manipulator would be unable to achieve the performance requirements at an acceptable cost, current APACTS design uses a series of three manipulators to position the system about the drydock, reach along the hull, and maintain proper standoff and motion. The Semi-Automated Paint Containment System (SAPACS) uses some of the APACTS technologies to achieve some of the APACTS goals at reduced cost.

3 Methods, Assumptions, and Procedures

This report reviews a manipulator system intended to improve worker productivity while capturing the paint overspray solids.

3.1 Coordinated Aerial Work Platform

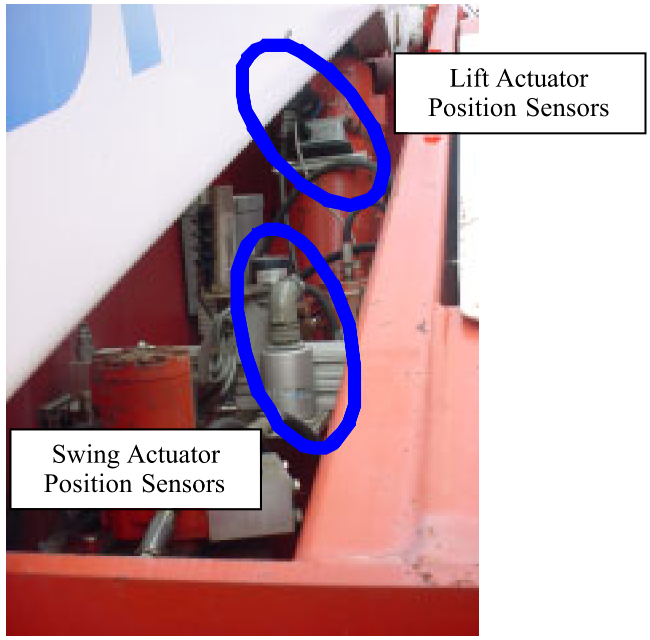
Commercial aerial work platforms are long actuated arms on a mobile base. The work platform's arm is retrofitted with sensors, servo controllers, and a supervisory controller to permit simultaneous coordinated motions of actuators. Coordinated motion enables the manipulator to follow the general contours of the hull surface and to coordinate actions with end-of-arm tooling.

Aerial work platforms are sluggish devices meant to carry workers to generally inaccessible areas. To the lift manufacturer, industry organizations, and government regulators, safety is a greater concern than speed or accuracy. The control valves use closed center spools that produce a broad stop region between the motion directions. The actuators incorporate holding valves to prevent rapid actuator movement in the event of power loss or operator error. These features protect workers on and near the work platform, but limit the system responsiveness.

Due to its large mass and the low bandwidth actuators, an aerial work platform has difficulty with small, quick motions. Around zero velocity, the slow response, the closed center valves, and the holding valves produce dead band, hysteresis, and other non-linear motion responses. However, when the spool is off center and the holding valves are open, the motion response is fairly linear. Therefore, a commercial aerial work platform can provide clean motions on long, continuous trajectories.

The commercial work platform has four degrees of freedom in five actuated joints. The degrees of freedom provide a 3D location (X, Y, Z) and rotation about the vertical axis. The fifth actuated joint maintains the vertical orientation of the final joint. The retrofit equips each actuator with a sensor to measure the actuator’s position and a micro-controller to monitor the position, receive commands from a supervisory controller, to compute the proper amount of oil flow to follow the command, and to drive the actuator’s oil valve. The micro-controllers form the servo level of the RCS control hierarchy [1].

Figure 2. Actuator Position Sensors



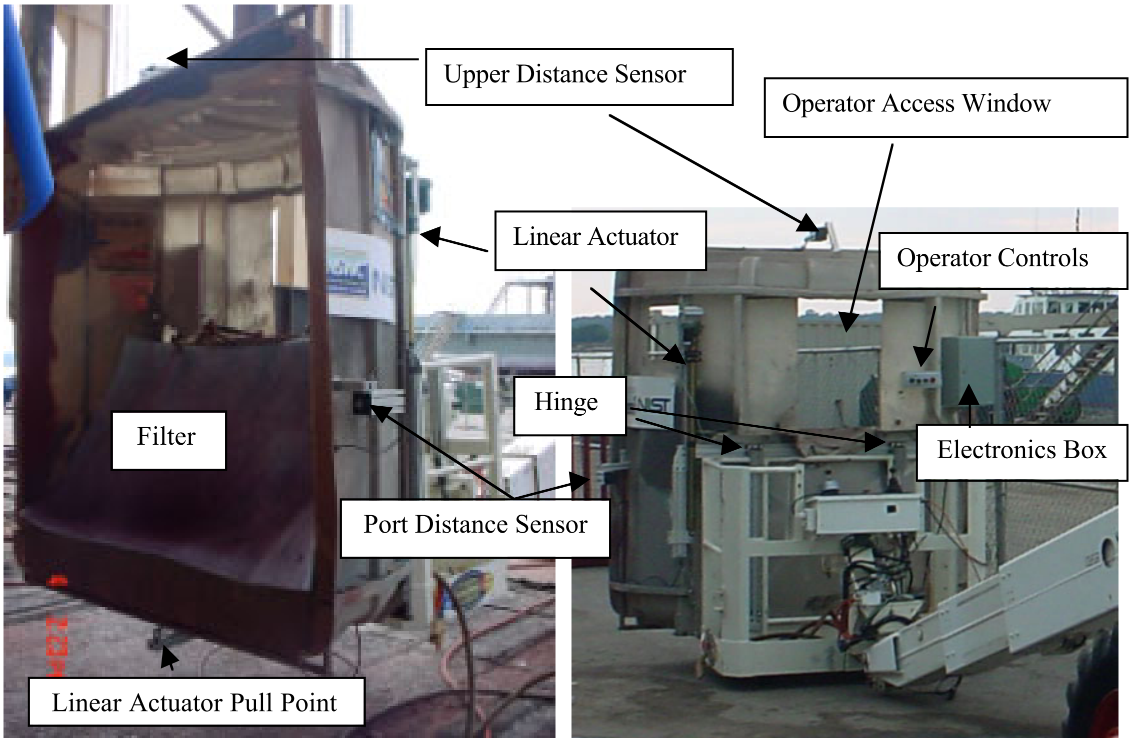
Software on a 486 computer performs the RCS primitive level control functions. The program accepts velocity commands from a supervisor, converts them into a sequence of position commands for the servo level, and issues those commands. The CAWP uses only the Servo and Prim levels of RCS. The next RCS level, E-Move, generates motions that are long in a dynamic sense, such as between two points. For a SAPACS-type system, the controller of the end of arm tool performs the E-Move functions and generates the Prim commands.

3.2 Enclosure

The SAPACS enclosure is a Spider Environmental Tank (E-Tank) from Flow International. The enclosure is a half cylinder shell with a window that provides access to the hull for the painter. When the enclosure is near the hull, a fan draws air from around the enclosure's perimeter and through a filter capturing the solids from the paint overspray. Researchers modified the enclosure to pitch about the mounting rail, to detect the position of the hull, and to interface with the CAWP.

Atlantic Marine Dry Dock Corporation provided a Spider environmental tank for this experiment. The Spider is a 2.4 m (8 ft) by 2.1 m (7 ft) by 0.9 m (3 ft) half cylinder, weighs 110 kg (420 lbs.) and includes a pneumatic fan to draw air through a 1.8 m (6 ft) by 0.6 m (2 ft) polyester filter. The Spider mounts to the front of an AWP basket with four crude hooks.

Figure 3. Modified Spider E-Tank



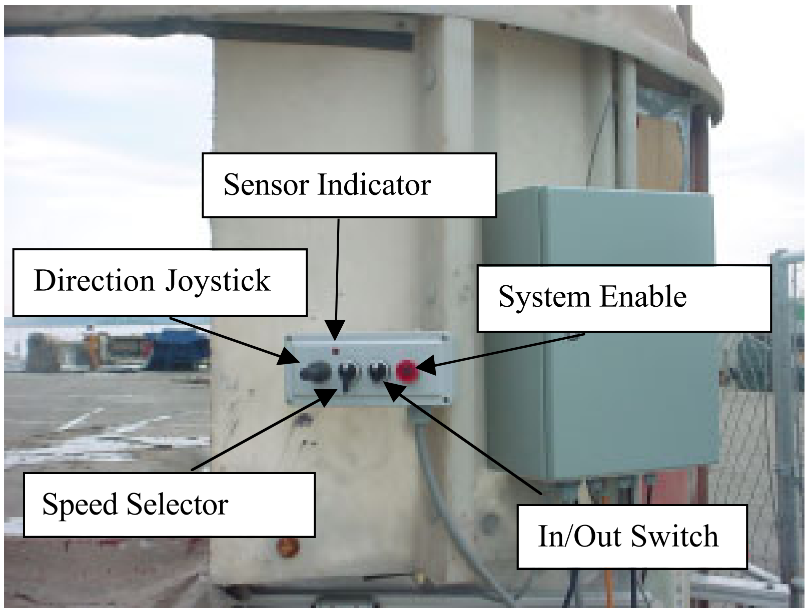
Researchers made four modifications to the Spider E-tank. A bolt-on mounting bracket with a hinged joint replaced the crude hooks. An electric linear actuator produced pitch motion about the hinged joint. Ultrasonic sensors measured the distance to the hull at three locations allowing the hull's relative distance, pitch, and yaw to be calculated. The final modification was a set of electronics boxes that included a tilt sensor, a motor amplifier, an operator control panel, a micro-controller, and a foot switch.

The linear actuator has a range of 0.81m (32 in). The actuator pulls the bottom of the enclosure away from the CAWP basket. Specifically, the actuator pulls on a cable that runs from a pulley at the base of the enclosure to the end of a rod that extends from the bottom of the basket. The actuator generates 0.31 rad (18°) of pitch motion.

3.3 Operator Interface

The operator control panel contains two knobs, one joystick, one button, and two indicator lights. The joystick has four possible positions that correlate to the four directions that the enclosure can command the CAWP to move: up, down, left, and right. The speed knob has three positions for selecting one of three pre-programmed speeds. The in/out knob commands the enclosure move towards or away from the hull if the foot switch is pressed, or to pitch the enclosure if it is not pressed. The button engages the controller when in the out position and shuts off the commands to the CAWP when depressed. The indicator light co-incident with the system button is dark when there is no power to the enclosure, flashes when there is power but the CAWP is not ready to receive commands, and is steady when the CAWP is ready. The second indicator light gives the status of the three ultrasonic sensors. The light is dark when none of the sensors are within 0.8 m (30 in) of the hull, flashes when one or two are within range, and is steady when all of the sensors are tracking the hull.

Figure 4. Operator's Interface



The operator interface provides minimal information and few options for the operator. This allows the operator to learn the system quickly.

3.4 Electronics

Mounted to the right of the operator's interface is the electronics box. The box contains a tilt sensor, a motor amplifier, a power supply, and a micro-controller. The tilt sensor gives the vertical direction of the enclosure and is used to determine the direction the CAWP should move the enclosure. The motor amplifier provides power to the linear actuator. The power supply provides 12v for the micro-controller and 24v DC power for the tilt sensor and three distance sensors. The micro-controller reads the sensors and the interface, computes the desired directions, and commands the actuator and CAWP.

The micro-controller is a PK2200 from Z-World Engineering [2]. The controller uses an 18.4MHz Z180, 8-bit processor and has 14 bits of digital output and 16 bits of digital input. A four-channel analog to digital conversion card, a touch panel with twelve buttons, and a 2x20 character LCD augment the base controller.

The digital input lines sense the position of the operator interface switches, the foot switch and the communications line with the CAWP. Four digital inputs detect the desired transverse motion direction. Two digital lines select one of three speeds. Two more lines command an approach or retract motion. One digital line each senses the system command, the foot switch, and the communications with the CAWP.

The digital output lines command the motor amplifier and communicate with the CAWP. The two indicator lights each derive from a digital output line. Four outputs command the motor amplifier for the linear actuator. These lines drive relays that connect isolated preset voltages to the amplifier's command wire. The scheme permits two speeds for each motion direction: a slow and a fast out, and a slow and a fast speed in. A single digital output line communicates to the CAWP via a bus.

The CAWP uses a Seriplex Sensor Bit Bus [3]to communicate between the CAWP actuators, the coordinating controller, and the CAWP's sensors. The SAPACS enclosure taps into this bus. Seriplex is a highly reliable, relatively slow, limited bandwidth, multi-drop, deterministic communications bus. The reliability and determinism are the overriding desirable features. Even the speed and bandwidth are advantageous to this application. Seriplex uses a single clock line and a single data line. Each node counts the pulses on the clock line and places its values on the data line in turn. Therefore the enclosure's controller uses one digital input line to count the clock line and one digital output line to place values on the data line.

The controller software reads the three distance sensors, computes the relative yaw and pitch, and commands the linear actuator to reduce the pitch. With the pitch angle reduced, the tilt sensor provides the angle of the hull relative to the horizontal. The angle, the difference between the actual standoff and the desired standoff, the yaw, and the operator indicated speed combine to form the command to the CAWP. The enclosure's controller sends the command as a desired velocity to the CAWP at 2 Hz. The 4 dof command is relative to the CAWP's basket including in/out, up/down, left/right, and rotation about the vertical.

The final function of the enclosure's controller is to modify the operating parameters. The supervisor uses the buttons and display to set the parameters used by the operator. The supervisor may set the selectable speeds, the standoff, the four linear actuator motor thresholds, accelerations, and the approach speed. The supervisor uses the same interface to calibrate the sensors. Each sensor uses a two-point linear calibration. The controller interface is more extensive and more complicated then the operator interface. However the operator does not need to use this interface for the daily operation of SAPACS.

3.5 Operation

Enclosure modifications produce a simple and convenient method for the operator to control the motion of the enclosure along the ship hull. The operator maneuvers the enclosure to a point along the hull with the standard controls provided on the commercial lift. The operator uses the lift's rotate actuator to align the enclosure's yaw axis and the enclosure's in/out switch to align the pitch axis. Once the sensor light indicates hull detection, the operator uses the in/out switch with the foot pedal to bring the enclosure to within the proper distance of the hull. The operator then selects the desired speed and direction. The painter then prepares the spray gun and steps on the foot pedal. The SAPACS moves along the hull in the direction and at the speed specified.

The painter paints as per normal procedures as new surface constantly moves in front of the access window. SAPACS adjusts the enclosure tilt, yaw, and motion direction to follow the curvature of the hull. The operator does not need to stop painting to relocate the enclosure until the end of the vertical swath. Furthermore, SAPACS maintains a more consistent standoff from the hull which would improve the overspray capture.

Generally, the painter paints faster than the SAPACS moves. The additional time allows the painter to perform wet film thickness (WFT) tests and to monitor the SAPACS progress. When the swath is finished, the painter releases the foot switch and SAPACS stops.

3.6 Evaluations

The evaluation criteria were worker acceptance and productivity. Worker acceptance is a subjective criterion discernable through interviews with the painter. Productivity is the measure of coverage per time. SAPACS's intended worth is productivity improvement over the use of the E-Tank without the enhancements or coordinated motion.

3.6.1 Worker Acceptance

Worker acceptance is a purely subjective evaluation. For reasons explained below, this SAPACS prototype could not perform all desired functions. Therefore, the researchers informally queried the painter and supervisor regarding the utility and functionality of the system. Utility is the ability of the operator to use SAPACS as intended. The functionality is whether SAPACS performed its mission to maintain appropriate standoff and capture the paint overspray.

3.6.2 Productivity

Atlantic Dry Dock was unable to conduct a time and motion study during the 2002 evaluation period. However we can derive preliminary conclusions from prior experience, informal observations, and programming parameters. In section 4.2 we compare productivity for three operating scenarios: painting without an overspray capture device and painting with an overspray capture device with or without coordinated motion.

3.7 Evaluation Limitations

The SAPACS prototype uses an enclosure based on a Spider environmental tank and a Coordinated Aerial Work Platform based on a model ATR-60 from Snorkel, Inc. The devices were available, but not the best suited for the application. Unexpected interactions between the devices limit the performance of the final system. As a result, the SAPACS prototype could not make lateral motions, had restricted vertical motions, and could not move freely on the test dry dock.

The ATR-60 is a manufacturer's engineering machine that was made available to the researchers by Snorkel. It includes several experimental modifications that do not always enhance the lift's performance. Particularly, the ATR-60's basket rotate actuator is experimental and cannot easily move a loaded basket.

The enclosure (at 190 kg (420 lbs.)) and operator (approx. 80 kg (200 lbs.) exceed the unrestricted load of the CAWP's basket (note: the operating volume was restricted during testing to maintain safety) . In addition the enclosure mounts to the front of the basket increasing the torque requirements of the actuator.

Snorkel's modified rotate actuator is unable to move the enclosure. Therefore the SAPACS prototype cannot perform lateral (side to side) motions. This limitation also restricts the CAWP vertical velocity.

Access is further limited by the available dry dock. The test dry dock has a wooden plank deck which can support a 12 m (40 ft) aerial work platform but not an 18 m (60 ft) machine such as the ATR-60. This limitation requires the SAPACS to access the ship hull through the dry dock's wing walls (a fence of steel girders). The SAPACS prototype can paint at most three vertical swaths before the operator must relocate the base. The motion, speed, and access limitations prevent a full evaluation of the prototype.

Due to the access limitations, the comparison area is a single, 7.3 m (24 ft) tall swath. When painting without coordinated motion, the painter positions the aerial work platform at successive positions along the swath. At each position the painter paints a section of the hull. A painter un-encumbered by the capture device reaches further both horizontally and vertically and paints larger sections. The total area of the swath is the sum of the areas of the sections. With coordinated motion, the painter paints one stationary section and the remainder of the swath at the rate that the SAPACS moves along the hull. The productivity is the ratio of the total area with the sum of the time required to paint the sections and the time to position the painter between sections.

4 Results and Discussions

4.1 Operator Perception

Atlantic Marine's painter and supervisors were positively impressed by the SAPACS prototype. The operator's perception of SAPACS was a combination of good and needs improvement: the operator learned the controls quickly but the SAPACS ran too slow. However, Atlantic Marine continued to use the prototype for two months following the test.

Figure 5 SAPACS in use on a DDG at Atlantic Marine Dry Dock

On November 3, 2002, researchers spent three minutes explaining the operator interface to the painter. He requested the instructor follow in another boomlift to help him on the first swath. However, the instructor took five minutes to bring the second lift into position and the painter had already started painting. The controls were sufficiently intuitive for the painter to use.

The painter had significant idle time. The painter spent only 20 % of the time painting. The painter spent the other 80 % waiting for new hull areas to move under the enclosure. Some free time is required for the safe operation of the system and for proper paint application and evaluation. However, the test velocity of 3.8 cm/s (1.5 in/s) was too slow for this painter.

The slow speed inadvertently encouraged the painter to paint to the limits of the enclosure. Some of these efforts overwhelmed the air capture system and released a small amount of overspray into the surrounding environment. The amount was not evaluated as part of this effort.

4.2 Productivity Advantages

The productivity evaluation is limited by the ship access restrictions and the absence of hard data. The estimates given in Table 1 below are based on some limited preliminary data, casual observations, and known programming parameters. The evaluation used identical swath heights to enhance the comparison. The researchers selected other parameters based on the technique used. For each technique, the swath width is the same as the painter's reach. Each alternative considers a single vertical swath for comparison with the access limitations of the SAPACS concept prototype.

Table 1. Production Estimates

	Units	Without Overspray Capture	With Overspray Capture	
			w/o Coordinated Motion	w/ Coordinated Motion
Swath Height	m (ft)	7.2 (24)	7.2 (24)	7.2 (24)
Swath Width	m (ft)	3.0 (10)	1.8 (6)	1.8 (6)
Block Height	m (ft)	2.4 (8)	1.8 (6)	1.8 (6)
Block Size	m^2 (ft^2)	7.2 (80)	3.2 (36)	3.2 (36)
Block Paint Time	s	36	24	24
# of Blocks		3	4	1
# of Relocations		2	3	n/a
Relocation Time	s	30	60	n/a
Traverse Rate	cm/s (in/s)			3.8 (1.5)
Total Area	m^2 (ft^2)	22.3 (240)	13.4 (144)	13.4 (144)
Total time	s	170	290	170
Production Rate	m^2/hr (ft^2/hr)	470 (5000)	170 (1800)	280 (3100)

The middle column of Table 1 provides an estimate of the productivity of a painter using an aerial work platform without an enclosure. The painter's reach dictates the block height and width. The wider swatch reflects the painter's freedom to move sideways in the lift's basket. The Block Paint Time derives from an observation of the painter taking 2 seconds to paint a stripe (both vertically and horizontally) and the overlap between stripes providing a net stripe width of 0.3 m (1 ft). The Relocation Time reflects the time required to put down the spray gun, take up the lift's controls, maneuver to the next block, and take up the spray gun again. The Production Rate of 470 m^2/hr (5000 ft^2/hr) for a single swath compares favorably to a generally accepted overall painter production rate of 440 m^2/hr (2500 ft^2/hr).[4]

The fourth column of Table 1 estimates the production rate for a painter using a lift equipped with an overspray capture enclosure, but without coordinated control of the lift's actuators. The size of the enclosure constrains the painter's motions and dictates the block size. Therefore, while the block is only half the size of the free painter, the time required to paint the block is two-thirds. The relocation time is significantly greater due to the requirement to carefully orient the enclosure to the hull to allow the overspray capture system to function. The productivity rate indicates the use of a containment enclosure reduces the painter's productivity by more than half. This conclusion matches previous experience by the yard personnel.

The final column of Table 1 reflects a painter's productivity using SAPACS. The block size and speed are the same for the previous paragraph. The Traverse Rate is the speed at which the enclosure follows the hull. The Traverse Rate value shown is the programmed value during the experiment. The resultant value falls between the painter without overspray capture and the painter with capture but without coordinated motion. While the final value does not reach the un-encumbered painter productivity, the improvement over the current portable enclosure is dramatic.

From table 1, developers can calculate the traverse speed required to return the painter to his un-encumbered production rate. For example, if the containment enclosure is the same size as the prototype enclosure, SAPACS covers 470 m^2/hr when the enclosure moves at 6.9 cm/s (2.7 in/s).

5 Conclusions

To comply with emerging environmental rules, shipyards must, or will soon be required to, control paint overspray emissions. Current compliance methods, such as static shrouds over large portions of the ship, are prohibitively expensive. Portable containment devices have the potential to achieve the required emissions control. However, static portable containments have a severe adverse impact on productivity, reducing productivity by more then 50 %.

By adding coordinated motion to the aerial work platform's actuators, SAPACS improves productivity. The ultimate productivity is a function of the enclosure size and the speed across the hull surface. With an aptly sized enclosure, actuators, and improvements to sensors and servos, SAPACS can restore the productivity lost by the use of the enclosure.

Furthermore, SAPACS is a non-invasive form of automation. SAPACS automation is a manageable step from equipment commonly used in the shipyards and does not require significant alterations to operations and procedures. Shipyard workers rapidly, if not immediately, recognize the advantage to their work environment. In summary, the SAPACS concept works and the shipyard personnel appreciate its potential.

6 Recommendations

A definitive test was not possible with the concept prototype. The CAWP was too heavy to be driven on the drydock floor thus limiting the hull area that could be tested. The E-Tank was too heavy for the CAWP to turn. This severely restricted the lateral movement of the SAPACS. I recommend building a second prototype based on a 12m (40 ft) aerial work platform and a lighter enclosure.

The interface used in the current prototype is not extensible to other applications. The enclosure system connected directly with the CAWP's control bus. This approach would limit future automation efforts by aerial lift manufacturers. All parties in automation should be as free as possible to improve and develop their components. A generic interface between the aerial lift and the tool is therefore required. A second prototype should be constructed with a generic interface between the CAWP and the enclosure based on IEEE 1451 [5] or similar data transfer standard.

A shipyard or central authority such as a Center of Excellence should retain the second prototype after the productivity and worker acceptance tests. Prototype availability encourages further familiarization with the system and permits increased utilization. The manipulator portion of SAPACS is an enabling technology that may be useful in solving other shipyard access problems.

7 References

1. The RCS Handbook, V. Gazi, et al, John Wiley & Sons, Inc., New York, NY, 2001, pp70..73.

2. Little Star C-Programmable Minature Controller Technical Referenca Manual, Z-World Engineering, Davis, CA,1995.

3. Seriplex Intelligent Wiring System, Square D Company Catalog No. 833OCT9601R4/99, June 2000.

4. Carderock Division, Naval Surface Warfare Center, SOL N00167-97-SS-R1, "Mechanical Ship Hull Paint Application System For Use in Drydock", Commerce Business Daily, April 10, 1997.

5. IEEE Standard for a Smart Transducer Interface for Sensors and Actuators – Transducer to Microprocessor Communications protocols and transducer Electronic data Sheet (TEDS) Formats, IEEE Std 1451.2-1997, IEEE Instrumentation and measurement Society, New York, NY, September 25, 1998.