CONCEPTUAL DESIGN OF A REMOTELY OPERATED VEHICLE FOR BEACH SURVEYING

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EXECUTIVE SUMMARY

This project addresses the conceptual design of new technology for conducting topographic surveys in the coastal zone. The central component of the system is a remotely operated, semi-autonomous, amphibious vehicle that is specifically designed for use in the surf zone. Work included 1) a literature search for existing technology, 2) conducting a workshop attended by experts in surf zone surveying and potential users of the system, 3) extensive telephone and written contact with experts in the fields of coastal engineering, surveying, all-terrain vehicles, power systems, ocean systems design, guidance of marine vehicles, and robotics, 4) development of a set of design and operation requirements the new surveying technology, 5) development of the conceptual design for the ROV system, 6) a literature search of model studies and methods for predicting loads induced by breaking waves, 7) preliminary design calculations for power requirements and vehicle stability, and 8) a preliminary cost estimate.

BACKGROUND

The Need for Data

The ability to effectively manage the coastal zone is for the most part determined by the quality of the tools available to aid in the decision making process. Efforts to improve our basic knowledge of the land-sea interface and to develop better tools with which to apply this knowledge, are continually hampered by a lack of viable and cost-effective means of conducting routine operations in the high wave energy environment of the surf zone. These operations include 1) site investigation for recreational, biological, and sometimes even historic resources, 2) bottom topographic surveying, 3) dredging and other methods of earthmoving, 4) rubble mound, concrete and pile construction, and 5) structure inspection. Of these, topographic surveying is the most fundamentally important, as survey data of high accuracy and resolution is essential to many other activities.

A fundamental component of coastal zone management is the ability to model and predict the effects of hurricanes and other high energy events on the beach. Development, calibration, and verification of these models requires accurate, high resolution surveys conducted repeatedly before, during, and after major storms. However, due to limitations imposed by operating conditions, mobilization time, and the costs of present beach surveying technology, efforts to collect these short-term data sets have been frustrated.

Many important coastal management programs and engineering projects also require the support of high quality data collected over large areas for extended periods of time. In the State of Florida, such programs include 1) the Coastal Construction Control Line Program, 2) an ambitious beach restoration and renourishment program, and 3) the processing of permit applications for coastal construction and dredging. This data is needed to document cumulative effects of storms, beach recovery, and cyclical and long-term trends (especially those associated with sea level rise). To address these needs, the Florida Department of Natural Resources, Division of Beaches and Shores operates the most comprehensive large-scale beach monitoring effort in the nation. The need for more survey data is ever-expanding however, and so there is a continuing effort to seek technology that improves cost efficiency and accuracy.

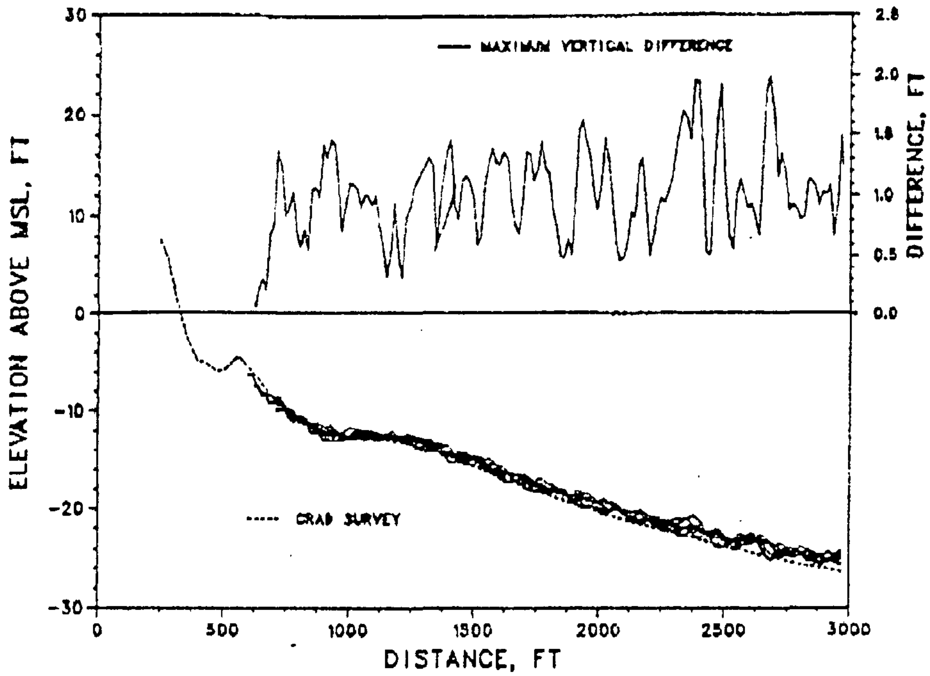
Present Technology

Common practice in beach surveying utilizes standard land survey techniques landward of wading depth. Seaward of this point, three methods have typically been used: 1) a boat equipped with a recording fathometer and mini-ranging system is brought in as close to the beach as safely possible, 2) the prism cluster for an electronic "total station" surveying device is attached to the mast of a sea sled, which is then towed along the bottom in the surf zone using a boat or amphibious landing craft (LARC), and 3) a shuttle that vertically tracks the beam of a shore-mounted laser level is carried by a LARC, measurements from which are added to those from a fathometer.

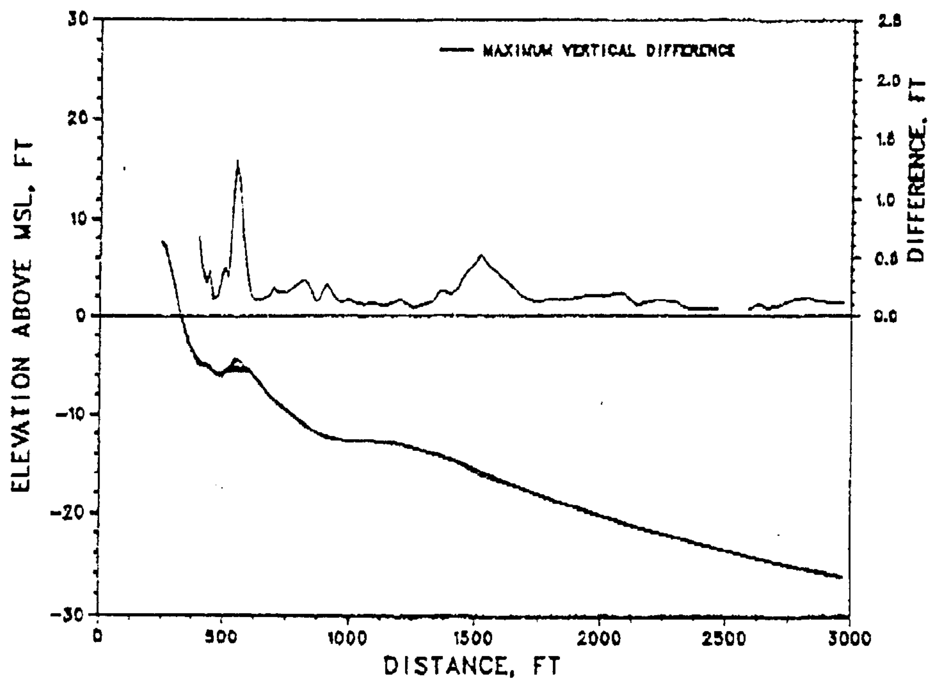
Because they employ boats or other floating platforms to traverse the surf zone, all of these methods are restricted in use to times when the wave climate is relatively benign, generally the breaker height must be less than 1 m. This survey window is quite restrictive for many coastlines. They also require a large support crew, and incur substantial mobilization/demobilization costs. In addition the first method, which is the most common of the three, often results in a gap in the transect over the most active region of the beach profile. This method is subject to fathometer errors induced by the boat's movement in the waves and changes in water temperature, and also requires estimates of the tide stage (Clausner, Birkemeier, and Clark, 1986). Survey closure is also a problem if the onshore and offshore portions of the survey often are not conducted concurrently.

A limited number of specialized vehicles have been developed for operation in the surf zone under more energetic conditions, and include one built by the Great Lakes Dredge and Dock Company and another by the U.S. Army Coastal Engineering Research Center (CERC). These vehicles are large tetrahedrons, nominally 10 m high, which ride on three hydraulically driven wheels. An engine, hydraulic pump, reservoir, controls, and instrument prisms are carried on top of the vehicle and remain above the sea surface. An onboard operator is required however, and because of the limits imposed by vehicle stability they are confined to operations in breaker heights less than 2 m. Even so, unexpected encounters with soft mud and holes have caused them to tip over during routine operations. These vehicles do provide the means to collect survey data that is at the state-of-the-art in resolution and accuracy, and have proven themselves to be extremely cost-effective when compared to the standard methods described above. Birkemeier and Mason (1984) report that CERC's Coastal Research Amphibious Buggy (CRAB) cut the cost of a single bathymetric survey of 26 profile lines from $35,000 down to $2,000, mostly due to personnel and time reductions.

Clausner, et al. (1986) intercompared the performance of the CRAB, sled, and boat/fathometer systems, along with an experimental "hydrostatic profiler" described in Seymore, Higgins, and Bothman (1978). Figure 1 shows the results of repeated surveys of the same profile with the CRAB and with a digital fathometer system. Note the large variability in the fathometer data. As indicated by their findings, although vehicles like the CRAB are a major step beyond the other systems in terms of the wave climate in which they can operate, these large self-propelled vehicles are not widely used due to 1) large initial expense, 2) large mobilization costs, 3) the still somewhat restrictive survey window imposed by operator safety in large waves, and 4) their inability to recognize and negotiate soft mud, steep slopes, and obstructions. The CRAB would cost an estimated $150,000 to build at present day, and because it weighs 18,000 lbs. and cannot be dismantled, it cannot be moved from the Field Research Facility (FRF) in Duck, North Carolina in a cost-effective manner. Storm conditions are often beyond the safe operating window, and some nearshore regions contain natural or man-made obstructions, or soils too soft to operate effectively with these vehicles.



a) Envelope of six digital fathometer surveys.



b) Envelope of five CRAB surveys.

FIGURE 1 - Comparison of repeated survey results using a) boat/fathometer and b) CRAB systems. (Figures from Clausner, et. al, 1986)

OBJECTIVES AND METHODS

The overall goal of any surf zone surveying system is to perform fast, accurate, high resolution surveys cheaply and efficiently. The system must also be easily transported, and must operate in a wide variety of wave, weather, and bottom conditions. Given the inability of boats and other surface craft to effectively conduct routine operations in breaking waves, and the cost, mobilization, safety, and mobility problems of the large CRAB type vehicles, it appears that a more viable and cost effective methodology is required in order to fulfill data requirements. The objectives of this research effort were therefore to:

A) Identify a basic approach/system that would significantly improve beach surveying technology.

B) Establish a specific set of design requirements for the system.

C) Develop a conceptual design that satisfies these requirements.

D) Devise a research and development plan that will validate the design.

To gather the background information needed to achieve the above objectives, a literature search was first conducted to identify existing beach surveying capabilities; plus, a workshop was held at the Field Research Facility to tap the vast experience of FRF and Corps district personnel and to seek their opinions and recommendations. During the course of this project, input was sought from approximately 30 manufacturers, private consultants, and state and federal agencies that have expertise in surveying technology, coastal engineering, and ocean engineering systems. A list of those contacted is provided in Appendix A. These experts provided insight on data needs, available technology, costs of system components, and cost restrictions and feasibility of the proposed system.

APPROACH

In the original proposal it was envisioned that the beach survey vehicle would be similar to the CRAB in concept, but with the added capability to dismantle it for transport to any site. However, one of the conclusions of the workshop and personnel at FDNR was that such a system still could not overcome problems with beach access, submerged obstructions and soft bottom, and the inherent danger of operating a manned vehicle in the surf zone. It was therfore necessary to identify a more viable approach.

In the past few decades, the development of remotely operated vehicles (ROVs) has greatly expanded man's abilities to explore and function in a broad variety of harsh environments. Of particular note is the extensive use of ROVs in the offshore oil and sea-floor mineral industries, where they have played a major role in increased productivity. ROVs and mobile robots have been developed to operate in the vacuum of outer space, under lethal levels of heat and radiation, and in environments contaminated by toxic chemicals and hazardous micro-organisms. In short, the whole purpose of an ROV is to remove the human operator from a dangerous environment. Because the surf zone is arguably the most difficult and dangerous marine environment in which to operate with conventional equipment, the consensus of expert opinion is that the concept of a ROV is particularly appropriate to this problem. Also, because the need for an onboard operator is removed, the ROV can be much smaller than a CRAB type vehicle, thereby avoiding problems with beach access and mobility. The approach using a ROV is adopted accordingly, and so design requirements can now be established.

SYSTEM REQUIREMENTS

A review of the literature on existing beach surveying technology, the input from those on the contact list, and the past beach surveying experience of the PIs and the attendees of the workshop, was used to determine the characteristics and requirements of the proposed ROV system. This experience encompasses all existing nearshore surveying hardware and techniques, both conventional and unconventional. Eleven primary requirements were established:

1) Accuracy and high resolution are needed to maintain the value and reliability of the survey data. The positioning hardware/methodology should be accurate, both vertically and horizontally, over long distances. Consequently the frequency at which the gear must be set up and taken down is reduced, thereby reducing costs. The ability to perform data analysis and plotting on site is also desired, which will enable important topographic features to be identified immediately and complete coverage of the study area ensured.

2) Increased survey speed is required to reduce manpower costs, thereby allowing more detail in surveys and expansion of monitoring programs. The vehicle should have a maximum speed of approximately 2.2 m/s (5 mph), and the surveying hardware/methodology employed must minimize the time required to take an individual measurement.

3) The ROV must be able to operate in 2 m breaking waves and out to water depths of 10 m. These conditions match those of the CRAB and are necessary for expanding the survey window, and to reach depth of closure for sand transport.

4) A system for hazard recognition and avoidance is required to protect the survey operation from costly down-time due to entanglements and damage to the vehicle. The ROV operator should be assisted by systems that enable him to recognize holes, reefs, debris, etc., and maneuver over or around them.

5) In the event the vehicle breaks down or does become entangled, a system for self rescue is needed. Without outside assistance, the operators should be able to first activate a rescue system that lifts the vehicle from the bottom, and then retrieve it to the beach to make repairs.

6) Continuous operation for at least four hours is needed to conduct uninterrupted surveys and maintain efficiency.

7) Mobilization/demobilization must be a top priority during design if the technology is to be an improvement over the CRAB or sled systems, and for it to receive widespread use. The vehicle must be easily transported between job sites using conventional means, and quickly set up for operation.

8) Beach access is a major factor in vehicle design because most beaches are blocked by buildings, dunes, or vegetation. The ROV system must be able to utilize narrow walkways and dune crossovers, which are the only common and reliable means of access.

9) In order to minimize costs, no more than three personnel are required to transport, operate and support the system.

10) Low fabrication cost is of course desired; in general less than $50,000 for the vehicle alone. This guideline was established by potential users in private industry and district personnel of the Corps of Engineers.

11) The design must be simple, and the vehicle fabricated from commercially available components. This will facilitate repairs, and allow the ROV to adapt to different surveying and research needs.

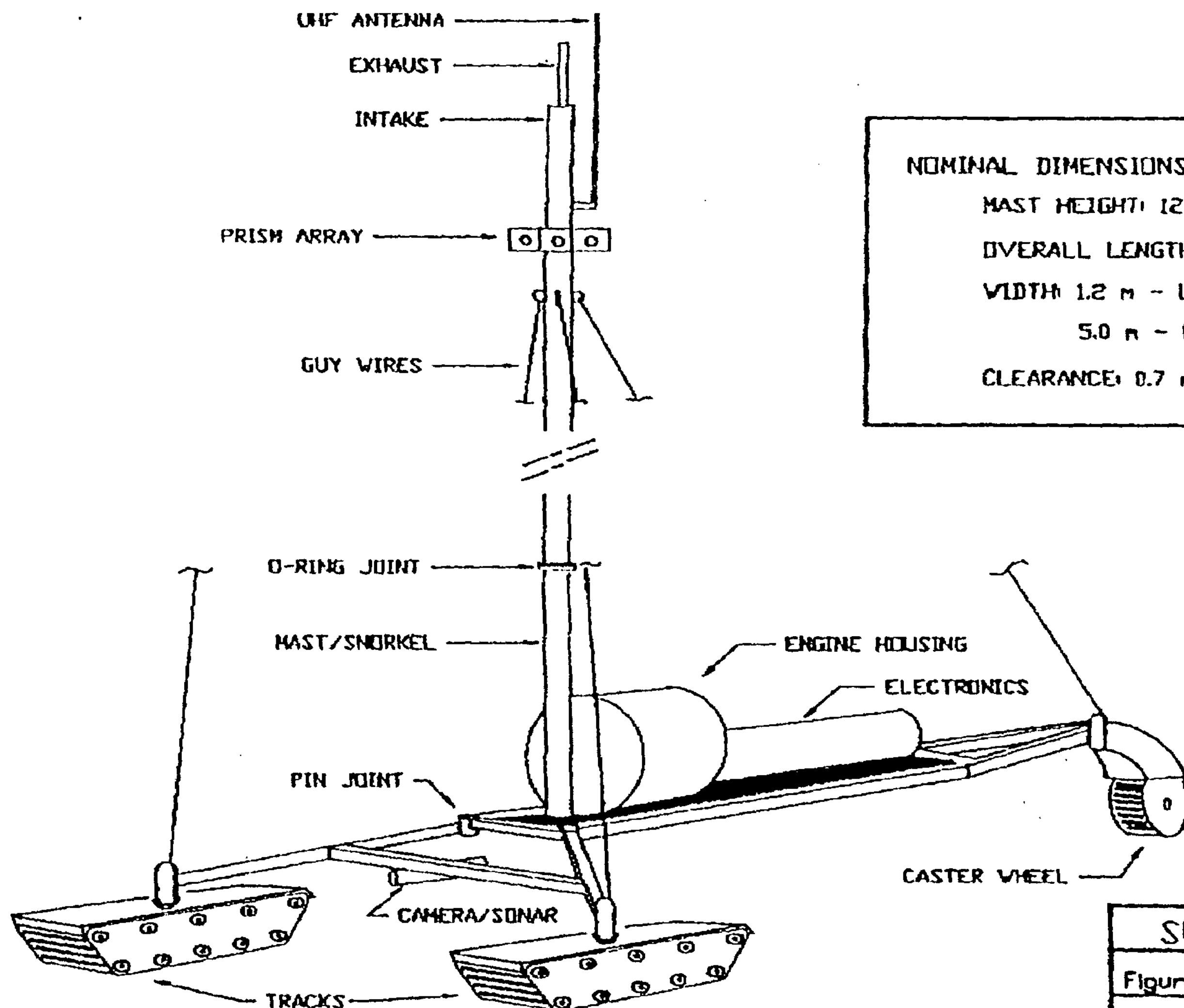
CONCEPTUAL DESIGN

To address the major system requirements listed above, the following conceptual design is proposed. Figure 2 is a CAD drawing of the remotely operated vehicle in its basic form. Its major features consist of 1) an aluminum frame which rides on two tracks and a caster type wheel, 2) a watertight housing, and 3) a snorkel. The rationale used in reaching this basic design, and the iterative procedure used to determine design loads and vehicle size is presented in Appendix B. Supporting calculations for motion-induced drag forces and breaking wave induced forces are provided in Appendix C and Appendix D, respectively. These calculations indicate that for the immersed weight of the vehicle (approx. 1500 lbs), the frame should be approximately 5 m wide. The two front arms have pin joints at each end so that they can be drawn together to reduce the width of the vehicle to only 1.2 m. This feature will allow the ROV to climb a straight stairwell or travel a footpath.

Tracks were chosen to provide propulsion because of their low contact pressure and proven mobility over a wide variety of terrains (Karafiath and Nowatzki, 1978). Unlike water-filled tires, tracks do not add unwanted buoyancy when the vehicle is submerged, nor do they add weight when on land. Each track is driven by a hydraulic motor, with steerage provided by a difference in their relative speeds. The free-spinning caster allows the vehicle to turn almost within its own length. Although a third track would aid in propulsion, this option was discarded because a complicated actuator and control system would be required to synchronize it with the other tracks.

The aluminum housing contains a diesel engine, hydraulic pump, fuel and hydraulic fluid tanks, computer controlled valves, and UHF transmitter/receiver. The housing is O-ring sealed, and designed so that its cover can be quickly removed for repairs and maintenance. A larger diameter section is necessary for the engine (0.75 m diam.) while to minimize buoyancy, a narrow section (0.25 m diam) will contain the remainder of the equipment.

The structural members of the frame are to be aluminum I-beam, with 4 in. web and 4 in. flange to support the dry weight of the vehicle. Tubular sections were not chosen because corrosion and cracks on inside surfaces are hidden from visual inspection. If necessary, cylindrical cowlings can be retrofitted to the



NOMINAL DIMENSIONS

MAST HEIGHT: 12 m

OVERALL LENGTH: 6 m

WIDTH: 1.2 m - Legs Folded
5.0 m - Operational

CLEARANCE: 0.7 m

SURF ZONE R.O.V.	
Figure 2: CONCEPTUAL DRAWING	
12/8/89	Drawn By: MJ/PS

I-beams to reduce drag. Aluminum is chosen to reduce corrosion in salt water, and to allow simple welding fabrication. The use of structural composites was considered, but rejected due to the likelihood of galvanic coupling, and high costs.

Initial power calculations based on drag on the vehicle at the design speed in deep water, presented in Appendix C, indicate a 20 to 30 hp. engine is required. The engine is to be water-cooled using an external heat exchanger. When extended operations in the dry are required, the engine is air-cooled by removing the housing cover. Concentric snorkels provide separate intake and exhaust, and serve as a positioning rod for a prism cluster and mast for the radio antenna. The intake also vents the housing, while the exhaust snorkel is connected directly to the exhaust manifold. When being transported to a site or maneuvered across a dune, the mast is disconnected at an O-ring joint.

The hydraulic system consists of pump, reservoir, manifold, valves, motors, and high pressure hydraulic line. The engine is attached to a variable displacement pump capable of 30 gal/min. A REXROTH axial piston swashplate pump is the preferred model. Two disc valve hydraulic motors (CHARLIN 6000 series) are used to drive the tracks. Due to their high torque, a gear box will not be required. The motors are controlled by a manifold port box (DAMAN) and two independent solenoid valves that vary both flow rate and direction (REXROTH "Hydronorma" model). This design for the hydraulic system will provide smooth turning and speed control, as well as allowing the vehicle to back up. The system requires 2000 psi hydraulic hose, and will have fluid filtration systems at both the intake to the manifold and the intake to the reservoir.

Guidance for the vehicle is provided by directional sonar and a low light level video camera. Signals are transmitted back to shore by the same onboard UHF system used to control the hydraulic valves. Both video and acoustic signals are displayed on a CRT so the operator has a real time video and acoustic image ahead of the vehicle. Experts indicate that there has been little experience with this type of equipment in the surf zone, and due to air bubbles and turbidity it is unclear how well these guidance systems will perform. It is expected that significant testing and development will be required for this component of the ROV system.

To conduct topographic surveys and aid in guidance, a self-tracking total station laser device is used to follow the prism array from shore and report its coordinates to a computer. This device is the key to increased survey speed and resolution. During the workshop at the FRF one such device was demonstrated in use with the CRAB. Previously it was necessary to stop for a minimum of fifteen seconds for the instrument to take each shot; but, with the self-tracking feature position was monitored continuously, and recorded once per second. The time required to cover one survey line was reduced by 40%, and was limited only by the maximum speed of the CRAB (2.5 mph). The number of data points recorded was increased from approximately 60 to over 250. With a self-tracking system, vehicle position can also be continually updated and plotted in a window on the operator's screen.

A tilt cube and electronic compass are also mounted on the vehicle, output from which are telemetered to correct the survey data in real time. This information will also provide the operator with the attitude and orientation of the vehicle, and help identify potentially hazardous situations.

In the case of vehicle breakdown or entanglement, a system of inflatable salvage bags is carried by the ROV. An actuator mounted on the mast allows a swimmer or rescue boat to start the inflation sequence. After raising the vehicle off the bottom, the ROV is towed back to shore by an inflatable boat. It is then pulled from the water by a truck or winch, and repairs made.

The ROV will most likely be transported to the job site on a small flatbed trailer (2 m x 6 m). The trailer is drawn by a four wheel drive truck or carryall, which also houses the data acquisition and communications equipment, and the operator. To set up the system, the ROV is driven right off the trailer and maneuvered over a stairway or other suitable beach access. The legs are then spread to their operational configuration, and the snorkel raised and guyed. The surveying device is set up on the dune and attended by a second crew member if necessary. The trailer also carries the inflatable rescue boat, while the truck is available to tow the ROV ashore if a breakdown occurs. A summary of the conceptual design is provided in Table 1.

TABLE 1 - DESIGN FEATURES OF REMOTELY OPERATED VEHICLE FOR BEACH SURVEYING

CONFIGURATION - Bottom crawling tripod (5 m x 6 m)

WEIGHT - Dry: 1,150 Kg (2,500 lbs)
Immersed: 680 Kg (1,500 lbs)

POWER - Diesel engine (20-30 hp), snorkel intake and exhaust, water cooled

DRIVE TRAIN - Hydraulic

PROPULSION - Tracks (2)

CONTROL - Computer-controlled solenoid valves

COMMUNICATION/TELEMETRY - UHF

GUIDANCE - Video, forward looking sonar

NAVIGATION/POSITION - Land based total station equipped with self-tracking laser

ORIENTATION - Electronic compass, tilt cube

RESCUE - Self-contained lift bag system

TRANSPORT - Pickup truck and trailer

COST ESTIMATE

The conceptual design of the ROV has been conducted in detail sufficient to make the cost estimate for equipment listed in Table 2. All components are commercially available except the caster wheel, housing, mast/snorkel, and frame. Fabrication requires welding and some machining, and should require roughly 120 man-hours.

TABLE 2 - COST ESTIMATE FOR EQUIPMENT

Engine	3,000
Pump	1,000
Reservoir	300
Hydraulic Hose	400
Fittings	500
Control Valves	2,500
Hydraulic motors (2)	2,000
Tracks (2)	4,000
Caster Wheel	500
Housing	2,500
Mast/snorkel	1,000
Frame	3,000
Control Computer	4,000
UHF Communications	2,000
Tilt cube	2,500
Digital compass	1,000
Trailer	2,000
Recovery system	800
Miscellaneous	1,000
Total for vehicle equipment alone	$ 34,000
Data acquisition and plotting hardware	6,000
Sonar	20,000
Video camera	5,000
Generator	400
FWD truck	28,000
Geodimeter surveying system with tracking laser	80,000
Total for peripheral equipment	139,400

FURTHER DEVELOPMENT AND VALIDATION OF THE DESIGN

Initial feedback from several users of conventional surveying systems, and experts in all-terrain vehicles and marine ROVs, indicates that the basic design of the ROV is a sound one. Tracked vehicle technology is well established, and diesel engines have been successfully operated underwater with snorkels since the turn of the century. UHF communication and control is also commonplace. Although drag on the ROV due to its own motion can be reliably calculated, the major question that remains open is vehicle stability in the surf zone in big waves. The results of a literature review made it clear that due to its complex shape, forces and moments induced on the vehicle due to breaking waves cannot be predicted reliably with the present state-of-the-art. As discussed in Appendix B, even model studies of simple small-scale vertical cylinders cannot provide valid estimates of breaking wave forces at full scale. It is therefore recommended that a full-sized mock-up of the vehicle be fabricated, in which the hydraulic system is run by an electric motor that is powered by an umbilical from the beach. Thus the diesel engine, control, orientation, and communications systems can be left out. The mock-up can then be deployed during as many storm events as possible, without risk to most of the expensive equipment. Such a testing program would firmly establish the allowable operating conditions of the vehicle. The mock-up can also be used to conduct mobility and beach access tests.

As mentioned previously, off-the-shelf sonar and video guidance systems may not function satisfactorily in the surf zone, and will require development and testing. Fortunately in conducting these experiments, the mock-up would serve as a unique mobile test bed with which to gain access to the surf zone.

SUMMARY AND CONCLUSIONS

Based on requirements for high quality nearshore survey data, and the recommendations of experts in the fields of coastal engineering, surveying, all-terrain vehicles, ocean systems design, guidance of marine vehicles, and robotics, the conceptual design of a system for nearshore topographic surveying has been presented. The central component of the system is a remotely operated, semi-autonomous, amphibious vehicle that is specifically designed for use in the surf zone. The system is easily transported, requires minimal support personnel, and has relatively low fabrication and maintenance costs. It is also readily adapted for use with a variety of existing land surveying hardware. If this technology were developed, beach surveys could be conducted faster, during higher wave conditions, at greater accuracy, and with higher resolution than with conventional technology. Cost savings of at least 75% are expected.

Aside from surveying, the ROV has great potential for use in conducting a number of other routine operations. These uses include deployment of various instruments, inspection tasks, and even robotic construction. It is possible that the proposed ROV system will eventually serve as a "workhorse" for the nearshore zone.

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APPENDIX A - CONTACT LIST

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Gahagan and Bryant, Inc. Grady Bryant (813) 831-4408	Nearshore Surveying (LARC and Laser Level System)
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Perry Oceanographic 275 West 10th St. Riviera Beach, FL 33040 Steve Mesuzik (407) 842-5261	Underwater Vehicles
Seacon / Brantner and Assoc., Inc. 1240 Vernon Way El Cajon, CA 92020 Chuck Richards (619) 562-7070	Underwater Cable and Connectors
Sea Engineering Robert Rocheleau (808) 259-7966	Survey Data Needs, Ocean Engineering Consulting

Star Power Services 5217 River Rd. Harahan, LA 70123 Dan Richards (504) 733-6897	Diesel Engines
Structural Composites Laboratory Florida Institute of Technology 150 W. University Blvd. Melbourne, FL 32901 Scott Lewitt (407) 768-8000 ex.6842	Marine Applications of Structural Composite Materials
Suma Corporation 2085 Castle Rd. Woodstock, IL 60098 Ted Jerominsky (815) 338-6705	Diesel Engines

APPENDIX B - DESIGN PROCEDURE

In order to provide a stable platform for accurate measurements, and to assure continuity across the land-sea boundary, it was decided that the ROV would be a bottom-crawling device. Next, options for power for the vehicle were identified and explored. Supplying power via an umbilical was not viable because of the desire to facilitate large operating distances, and the likelihood of entanglements; see Seymore, et al.(1978) and Clausner, et al.(1986). With it established that the vehicle must carry its own power plant, options for batteries, gasoline engines, diesel engines, and even the more esoteric Sterling engine and aluminum fuel cells were identified and investigated. From discussion with battery manufacturers and designers of propeller-driven ROVs (which require low torque and high rpm), it was determined that because propulsion for all-terrain vehicles requires high torque and low rpm (Karafiath and Nowatzki, 1978), batteries could not meet power requirements. A gasoline engine has an associated risk of fire or explosion, while Sterling engine and fuel cell technology are not yet established as reliable, cheap, and "off-the-shelf". Because power must therefore be supplied by a diesel engine, the need for a snorkel was established. Unfortunately, this exposes the vehicle to increased drag force and overturning moment, especially under conditions at the maximum design speed and depth. Such a surface-piercing staff is unavoidable in the design anyway, due to telemetry and positioning requirements.

At this point in the design process, it was necessary to estimate the loads the vehicle would experience during operation. Two types of loads are important: 1) the drag on the vehicle induced by its own motion through the water, and 2) the overturning force induced by the impact of breaking waves. Analytical methods for calculating drag forces due to unidirectional flow around idealized shapes are well established, and were followed during design (see Appendix C). To estimate forces on the vehicle induced by breaking waves, it was originally thought that small-scale model tests conducted in a wave flume would provide some insight. However, a literature review of experimental studies of forces induced by breaking waves on vertical cylinders (see References/Bibliography) indicated that due to scale effects, the results of testing with a small scale model of the ROV would have little meaning in regards to the stability of the prototype at full scale. As described by Apelt and Piorewicz (1987), this is because at small scale the requirement for Reynolds Numbers in the supercritical range cannot be met. In fact they recommend in their conclusions, "It is very desirable that experimental studies be carried out on breaking wave forces on full-size cylinders in real seas." This is the reason it is recommended that stability tests be conducted in the surf zone with a full scale mock-up of the ROV.

With the idea of inferring breaking wave impact forces from a model test eliminated, a literature review was performed to learn from available studies conducted at full scale, and to determine the state-of-the-art in methods for predicting these forces. Ross (1955), Hall (1958), and Kjeldsen and Akre (1985) presents results from tests of forces on vertical cylinders performed at full scale in large wave tanks, while the Shore Protection Manual (1984) and Swift (1989) present methods for calculating them. Although certainly the state-of-the-art in detail and sophistication, the method of Swift (1989) was found to be too computationally intensive for use in this conceptual study. However, the method recommended in the Shore Protection Manual (1984) was found to be more suitable to the needs of this project, and is calibrated to the large scale results of Ross (1955) and Hall (1958). This method is followed in Appendix D to calculate breaking wave loads on the vehicle, and these results in turn used to determine the required lengths for the legs.

The iterative procedure followed to estimate the required size and weight of the vehicle is as follows:

1) Assume a diameter for the snorkel, diameter for the engine housing, and frontal area for the frame and tracks.

2) Calculate the drag force on the snorkel, housing, frame and tracks at a speed of 2.2 m/s in a water depth of 10 m (Appendix C).

3) Calculate required horsepower (Appendix C).

4) Choose an appropriate diesel engine, check its dimensions to make sure it will fit within the assumed housing size, and that the assumed snorkel diameter will provide sufficient intake and exhaust.

5) Iterate steps 1-4.

6) Calculate the overturning moment due to impact of a 2 m breaking wave (Appendix D).

7) Estimate the approximate immersed weight of vehicle (Appendix D).

8) Determine splay required for immersed weight to resist overturning. Add ballast if necessary to reduce splay to manageable size (Appendix D).

9) Iterate steps 6-8.

10) Determine track length from dry weight and desired soil contact pressure.

11) Size structural members to carry dry weight of vehicle.

12) Check weight of structural members.

The design proceeded from the assumption of a snorkel diameter of 6 in. This was found to provide plenty of intake and exhaust, and did not have to be altered during subsequent iterations. The final iteration of the design loads are provided in Appendices C and D.

APPENDIX C - DRAG AND POWER CALCULATIONS

Drag Calculations

The drag force on an object moving at a constant velocity through a still fluid (or conversely unidirectional flow around a stationary object) is given by the expression:

$$F = 1/2 \rho C_D A U^2$$

where

F - drag force (Newtons)

ρ - mass density of seawater (1030 kilograms/cubic meter)

C_D - drag coefficient (dimensionless)

A - projected area of object (square meters)

U - velocity of object (meters/second)

Drag on Mast

Mast area is 0.15 m (6 in.) x 9.1 m (30 ft.) = 1.37 m^2

Reynolds number for flow field = $(2.2)x(0.15)/(9.3x10^{-7})$

$= 3.6x10^5$

therefore $C_D = 1$ (cylinder)

$$F_M = 1/2\ (1030)(1)(1.37)(2.2)^2$$

$$F_M = 3414\ N$$

Drag on Frame

Frame area is 0.1 m (4 in.) x 6 m = 0.6 m^2

Reynolds number for flow field = $(2.2)x(0.1)/(9.3x10^{-7})$

$= 2.4x10^5$

therefore $C_D = 1$ (cylinder)

$$F_F = 1/2\ (1030)(1)(0.6)(2.2)^2$$

$$F_F = 1520\ N$$

Drag on Engine Housing

Housing diameter is 0.762 m (30 in.)

Housing area is $\pi\ (0.762)^2/4 = 0.456\ m^2$

Reynolds number for flow field $= (2.2)x(0.762)/(9.3x10^{-7})$

$= 1.8x10^6$

therefore $C_D = 0.5$ (sphere)

$$F_H = 1/2\ (1030)(0.5)(0.456)(2.2)^2$$

$$F_H = 568\ N$$

Drag on Tracks

Track area is 0.356 m (14 in.) high x 0.61 m (2 ft.) wide $= 0.22\ m^2$

Reynolds number for flow field $= (2.2)x(0.61)/(9.3x10^{-7})$

$= 1.4x10^6$

therefore $C_D = 1.2$ (rectangular flat plate; h/w=0.57)

$$F_T = 1/2\ (1030)(0.22)(1.2)(2.2)^2$$

$$F_T = 658\ N$$

x 2 tracks = 1316 N

Total Drag Force

$$F_{Dtot} = F_M + F_F + F_H + F_T$$

$$F_{Dtot} = 6818\ N$$

Power Requirements

Power = Force x Velocity = 6818 x 2.2 = 15,000 Nm/s

1 horsepower = 745 Nm/s

Required power = 20.1 hp

Mechanical and hydraulic losses are in the range of 45 to 60%, therefore approximate total power required to run the vehicle is

20.1 x 1.5 = 30 hp

APPENDIX D - CALCULATION OF FORCES AND OVERTURNING MOMENT DUE TO BREAKING WAVE IMPACT

These calculations on based on the "worst case" scenario of a 2 m breaking wave striking the vehicle broadside. A reasonable estimate of the depth at which breaking takes place is the wave height, i.e. $h_b = 2$ m. Following the Shore Protection Manual, the force per unit length on a vertical cylinder due to the impact of a wave at incipient breaking is given by the expression:

$$f_{im} = 0.88 \rho g D H_b$$

where f is the impact force per unit length, D is the cylinder diameter, g is gravitational acceleration, and H_b is the breaking wave height. For the design conditions we find:

$$f_{im} = 0.88 (1030)(9.8)(0.15)(2.0)$$

$$f_{im} = 2665 \text{ N/m}$$

$$F_{im} = f \times 2.0 \text{ m} = 5330 \text{ N}$$

Because the engine and electronics housings are below the mean water level during this scenario, they are only subjected to the drag force induced by the water particle motion associated with the wave. From shallow water linear wave theory (see S.P.M.) this velocity is given by

$$U = (H_b/2)\times(g/h_b)^{1/2}$$

$U = 2.2$ m/s (coincidentally equal to the design speed)

Engine Housing

The length of the engine housing is required to be approximately 0.89 m (35 in.) to fit a 30 hp engine. Projected area of housing is therefore 0.76 x 0.89 = 0.677 m^2.

$$F_{lh} = 1/2 (1030)(1)(0.677)(4.9)$$

$$F_{lh} = 1708 \text{ N}$$

Electronics Housing

The diameter and length of the electronics housing are required to be approximately 0.2 m (8 in.) and 1.0 m (40 in.) respectively. Projected area is therefore 0.2 x 1.0 = 0.21 m^2.

$$F_{eh} = 1/2 (1030)(1)(0.21)(4.9)$$

$$F_{eh} = 530 \text{ N}$$

Overturning Moment

The base of the vehicle housings is to be 1.0 m above the bottom, which dictates that the appropriate moment arms for this calculation are:

$$L_M = 3.0 \text{ m}$$

$$L_{lh} = 1.0 + 0.38 = 1.38 \text{ m}$$

$$L_{sh} = 1.0 + 0.1 = 1.1 \text{ m}$$

The sum of the moments is

$$M = (5330)(3.0) + (1708)(1.38) + (530)(1.1)$$

$$M = 18{,}930 \text{ Nm}$$

Vehicle Splay

Estimating the immersed vehicle weight, including ballast, as approximately 6,672 N (1,500 lbs), the required splay for one leg of the vehicle is

(overturning moment / immersed weight) - (1/2 track width)

$$(18930 / 6672) - 0.305 = 2.5 \text{ m}$$

Therefore the total vehicle splay is 5 m. Calculations of the buoyancy of the vehicle housings indicates a buoyant force of 4,400 (1000 lbs). Therefore the dry weight of the vehicle and ballast is approximately 11,100 N (2,500 lbs).