The Deep-Sea Tortugas Shipwreck, Florida: Technology

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Between 1989 and 1991 Seahawk Deep Ocean Technology of Tampa, Florida, conducted the world's first robotic excavation of a deep-sea shipwreck, in this case lost in 405m off the Tortugas Islands in the Florida Keys, USA. The study of this merchant vessel from the 1622 Spanish Tierra Firme fleet required the development of cutting-edge technological solutions ranging from an appropriate research ship to a sophisticated Remotely-Operated Vehicle. The latter was custom-tooled with a specialized pump and suction system, which included a limpet device to lift delicate artifacts and a Sediment Removal and Filtration (SeRF) filtering unit to save small finds recovered during the extraction of sediment spoil. The Tortugas shipwreck's technology package successfully enabled 16,903 artifacts to be recorded and safely recovered.

1. Introduction

In July 1989 when the location of the Tortugas shipwreck was first identified using a Deep Ocean Engineering Phantom ROV (Remotely-Operated Vehicle), underwater technology was developing at a rapid rate due to vast budgets being made available for complex projects across the world. Between 1978 and 1988 the offshore oilfield industry had made significant advances in their capabilities for deep-sea work ranging from pipeline surveys to offshore oil rig support and inspection.

The navigational precision of the data demanded for rig support and the laying of oil pipelines needed to be to centimetric accuracy in critical areas near structures and lesser (1m) in open water. These systems were highly automated: data recorders only needed to press one or two keys to record all positional data and references to video, still photographs and anomaly identity. Seahawk chose to adapt recognized and well-developed offshore oil and gas technology to the recording and recovery of artifacts from the Tortugas shipwreck as the most realistic and efficient methodology for a scientific deep-sea excavation.

While some cursory exploration and salvage work had been accomplished on other deep shipwreck sites, the excavation of the early 17th-century Tortugas shipwreck represented the world's first comprehensive archaeological excavation of a deep-sea shipwreck entirely remotely using robotic technology. The project called for appropriately respectful technology suited to the removal of sedimentary overburden, accurate positioning and recording systems, as well as sensitive artifact recovery tools. The project resulted in the recovery of 16,903 artifacts, ranging from gold bars to ballast stones and extensive ceramics, animal bones, pearls and tiny seeds, and the procurement of an enormous quantity of scientific data in the form of video, still photographs and records. The Tortugas shipwreck excavation's pioneering technology package served as the backbone to the archaeological reconstruction of this shipwreck.

Fig. 1. The 86ft-long research vessel RV Seahawk.

Fig. 2. The Seahawk Retriever *in port. Photo: John Astley.*

Fig. 3. The Seahawk Retriever *anchored over the Tortugas shipwreck site on a four-point mooring. Photo: John Astley.*

Fig. 4. A DOE Phantom 300 ROV used for visual reconnaissance from the RV Seahawk.

2. Survey Equipment

The operation's platform used during the Tortugas shipwreck survey was the 26.2m-long research vessel *Seahawk* (Fig. 1), equipped with side-scan sonar, sector-scanning sonar, magnetometer, a multi-target acquisition/tracking system, an integrated navigation system, Remotely-Operated Vehicles, HF, VHF radios and a very long range cellular telephone. The integrated navigation system was capable of generating search grids and graphically displaying the real time position of the research ship. The side-scanning sonar (consisting of a Klein 590 paper recorder, a 100/500 khz towfish, a Sintrex high-resolution magnetometer and an EG & G magnetometer), a Mesotec 971 and UDI sector-scanning sonar, a Loran C Integrated Seatrac Navigation System, and a Track Point II Dynamic Relative Positioning System facilitated the initial survey.

The side-scan sonar featured transducers on a tow fish that emitted and received acoustic pulses, which were transmitted to the research vessel. The data from the Klein side-scan sonar tow fish (100/500 khz) were transmitted to a model 595 recorder for processing. The system was able to record a swathe of up to 300m to each side, depending on the frequency. Conditioned by density and material, features and objects rendered a dark silhouette created by acoustic shadows on thermal paper, which fed out of the recorder at a speed proportional to the tow fish's movements along the survey lines. The resulting image provided a detailed representation of the ocean floor features and characteristics: an accurate picture of a wide area, which could be interpreted to construct a three dimensional image of the seafloor's contours.

Aboard the RV *Seahawk* were three ROV's equipped with video and still cameras to provide visual access and documentation in deep water, and a manipulator device

Figs. 5-6. The initial visual wreck survey was accomplished using a Phantom DHD2 ROV (top) being launched by Scott Stemm, Dr. James Cooke, David Six and Steve Dabagian.

that enabled the mechanical retrieval of artifacts. The largest and most versatile of the ROV's was a Phantom DHD2, custom built for this project by Graham Hawkes of Deep Ocean Engineering. The DHD2 had a depth rating of 610m, a low-light color video camera and relatively simple articulated arm (Figs. 5-6). A Phantom 500, with a depth rating of 150m and a color video camera, was

Fig. 7. The 3-ton ROV Merlin built for the Tortugas shipwreck excavation; with its SeRF system hose and nozzle at front right, two manipulator arms and limpet suction device at center. Along the badge bar are two 35mm cameras and two 70mm still cameras.

a mid range ROV. Finally, a Phantom 300, with a depth rating of 90m and color video, functioned in shallow water (Fig. 4). The RV *Seahawk* was capable of holding station under its own power without anchoring by 'liveboating' the vessel during ROV operations.

Initial visual survey of the wreck site was accomplished using the Phantom DHD2 ROV (Figs. 5-6), which was equipped with a Mesotech 971 sector scanning sonar and was utilized to define the location and perimeter of the site. The ROV was linked to *Seahawk* via 610m of shielded 42 separate conductor umbilical cable (no single wire multiplex control system was available in 1990-91) and was fitted with two 250-watt halogen lights and two Panasonic CCD low light video color cameras to illuminate the site. The Phantom DHD2 had a single function manipulator arm to provide dexterity for the retrieval of artifacts and was equipped with an ORE multi-beacon, which emitted an analog signal received by a Trac Point II tracking system. DHD2, with dimensions of 0.6 x 0.9 x 1.2m, including its protector bars, weighed approximately 68kg and was propelled by six thrusters. The pilots flew the ROV using a 'joy stick' control and observation via a small TV monitor mounted in the control console. A 'co-pilot' managed the camera adjustments, recorders and manipulated the retrieval arm.

The launch system onboard the RV *Seahawk* consisted of a winch, an A frame, armored tether and depressor weight that allowed ROV operations to be conducted in depths of up to 600m of water. The ROV was free-swimming, relying on the depressor weight connected to the armored umbilical, with a 50m neutrally buoyant excursion tether from the depressor that provided a 100m footprint for the ROV.

The video survey of the Tortugas deep-water wreck initially revealed a shipwreck site measuring approximately 15m long and 10m wide characterized by wooden hull remains, piles of ballast stone and numerous 17th-century olive jars. All videotapes recorded throughout the excavation were, and continue to be, held for permanent reference.

3. Excavation Equipment

In order to commence excavations with suitable technology, a second vessel, the 64m-long *Seahawk Retriever*, was dispatched to the site in May 1990 (Figs. 2-3). Originally called the *Tera Tide*, this vessel was built in 1974 by Burton Shipyard, Texas, as a twin screw supply vessel for transporting and pump drilling mud in the oilfields of the Gulf of Mexico. Of welded steel construction, and with a flush deck aft and raised deck forward, a model bow, square stern and steel deckhouse, the ship was retro fitted for the Tortugas shipwreck excavation with low pressure Bratvaag winches for managing a four point mooring system (Fig. 3), cranes for hoisting equipment and artifacts, a billeting module for housing additional personnel, a complete suite of communications and security technology and a control module for the ROV. The *Seahawk Retriever* was equipped with living facilities for a 30-person crew (Appendix 2).

While manned submersibles capable of operating at the depth of the Tortugas wreck were available to the project, the relatively short duration capability of manned subs, the low power available in their DC systems and difficulty of working in heavy currents made such an approach to the site impractical. Seahawk considered robotic excavation to be the best solution to the unique problems of excavation at 400m depth. After lengthy consultation with archaeologists and subsea engineers, a large work ROV, nicknamed Merlin, was designed and constructed to the specifications laid out by Seahawk's technology team specifically for archaeological excavation in deep water. The system was manufactured by AOSC, formerly AMETEK Offshore Scotland, Ltd., of Aberdeen, Scotland (Appendix 1).

Merlin was fitted with advanced Schilling manipulators, a customized suction dredge, an acoustic long baseline positioning system and weighed approximately 3 tons out of water (Figs. 7-12). Buoyancy blocks of syntactic foam (to resists the crushing effects of pressure at 400m) made Merlin 272kg positively buoyant. The ROV had six hydraulic-powered positioning thrusters; vertically oriented thrusters allowed it to work above the seafloor without stirring up sand or silt. In other words, Merlin floated and used thrusters to push itself down, which enabled the system to hover safely over the site. Thrusters also held the ROV steady when artifacts were lifted. Either manipulator arm could lift up to 113kg without affecting Merlin's position in the water. One of the manipulators used a master/slave system controlled by a master replica of the manipulator at the surface desk; the jaw pressure could be dialed up to 500lbs or reduced to a few ounces. Positioning was determined and recorded by a system of long baseline transponders installed on the site, which communicated with transponders on Merlin and the ship.

Fig. 8. Cameras and strobe lights at the front of the ROV Merlin. Photo: John Astley.

Fig. 9. The SeRF (Sediment Removal and Filtration System) tool for sieving small finds custom-designed for the Tortugas shipwreck excavation and installed onto the rear of the ROV Merlin. Photo: John Astley.

A crew of three technicians operated the ROV from the control room onboard the *Seahawk Retriever* (Figs. 13-14) under the supervision of the project archaeologist. Video was relayed to the control room via fiber optic cable, where three 30in video screens provided a 180-degree view of the underwater excavation site. One Photosea 35mm camera and two 70mm cameras (oriented so that stereoscopic still photos of artifacts *in situ* were possible) provided still photography. Merlin's Schilling manipulators were made of titanium and included a five-function and a seven-function unit. Pilots watched events on the seafloor live in real time on monitors and commanded the manipulator arms using joysticks at the control console aboard the *Retriever*.

Figs. 10-11. The custom-designed receiver and venturi pump from the SeRF (Sediment Removal and Filtration System) unit installed onto the rear of the ROV Merlin (with an early prototype at top). Photo (Fig. 11): John Astley.

Fig. 12. The ROV Merlin docked onto the deck of the Seahawk Retriever*. Photo: John Astley.*

Fig. 13. The archaeological recording and datalogger room on the Seahawk Retriever *from where excavations were observed and documented. Photo: John Astley.*

Fig. 14. Monitoring archaeological operations on the Tortugas shipwreck from the Seahawk Retriever*. The top screens displayed sonar and navigation. The three middle colour screens revealed a very wide view of the site under investigation. The lower row of screens depicted compass, vehicle instrumentation and stern camera data, plus other cameras monitoring the ROV parts. In the foreground the datalogger runs four SVHS recorders and the logging system. Photo: John Astley.*

Fig. 15. A Sonardyne transponder, with the transducer at left and the hook release at right, all encased in a buoyancy jacket to facilitate recovery. Photo: John Astley.

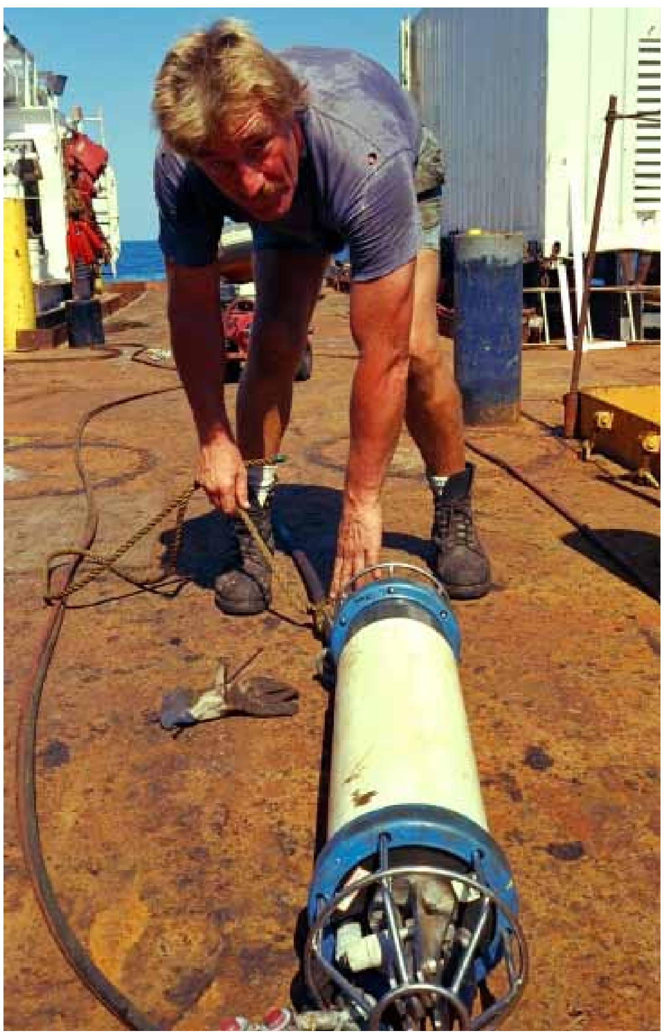

Fig. 16. Alan Crampton rigging a Sonardyne transponder for deployment. Photo: John Astley.

4. Operations

The approximate location of the Tortugas shipwreck in 405m of water was determined by a Loran C navigational fix obtained when the site was first discovered. To position the ship for the excavation, four Sonardyne Compatt transponders were placed approximately 200m away from the wreck perimeter, their positions at this stage not being critical (Figs. 15-16). Four large anchors were situated 1,600m apart in a box group around this position. These were connected by 30m of chain to a steel wire leading straight up to the surface, where they were attached to 3m-diameter mooring buoys. The ship connected its mooring winches to these buoys and wound itself into the middle of the array. It was imperative to use mooring buoys in this operation because if the research ship attempted to connect directly to the anchors in this depth of water it would have jeopardized the integrity of the wreck as the connecting wires could have swept across the site. The buoy system also allowed the vessel to hook into and release itself from the system without recovering the anchors.

The Sonardyne long baseline system used for positioning included a set of transponders that were placed in a seabed array and interrogated by the ROV, or the ship, to obtain positional information. Calibrating arrays of this type and gauging the precise distance between transponders on the seabed had always been an inherent problem. Traditionally this had been executed using transponders that 'ping' (transmit a single tone but no telemetry) and by steaming the ship around the site and interrogating the transponders to compare positions with surface radio navigation systems, thereby obtaining a calibration. This method produced a reasonable result in shallow water, where the temperature and salinity of the local water column was known and in an area where surface navigation facilities were good (bearing in mind that in 1989 GPS was not yet available).

The Sonardyne Pans system used on the Tortugas shipwreck project removed errors caused by distortion of the speed of sound in water due to the vertical water column. All of the transponders are 'intelligent': they passed information between themselves through water as sound, rather like the RS232 system used in computer telemetry. They possessed a vast repertoire of commands and abilities, which could all be controlled from the surface or by the ROV. The procedure designed for this system involved placing an array of four transponders in the optimum positions. The calibration procedure functioned as follows:

Figs. 17-18. Removing overburden on the Tortugas shipwreck using the SeRF system.

1. The transponders measured the temperature and salinity of the water at the seabed. This information was passed to the surface as data, and used to derive the speed of sound in water at the seabed level.
2. The transponders were then instructed from the surface to interrogate each other about 20 times each in all directions and between all paths between each transponder.
3. Each transponder that was interrogated replied to its interrogator. The total out and return time across the local seabed was sent to the surface as data.
4. At the surface a histogram was constructed of each interrogation path. From this the actual distance between any two transponders could be established to a high degree of accuracy. Any small error was then eliminated by iterating a 'best fit scenario' for the complete array. The result was a calibration that determined the relative positions of the transponders to better than 5cm spatial accuracy. No data relying on sound velocity was ever determined through the vertical water column, only horizontally through the water at the local work site.
5. When the system was calibrated, the array could be interrogated by the ROV on the seabed. The return times were collected by the vehicle's ROVNAV system and sent up the vehicle umbilical as data via a modem.

During the course of the excavation, using this system a repeatable recording accuracy of approximately 10cm for the ROV's position was obtained. The array could also be interrogated vertically through the water column from the ship via a transducer to place the ship within 5m for the launching of the ROV or retrieval of anchors.

A Navigation Camera was situated on the front of the ROV that looked down vertically to navigate movements safely. A video overlay system generated a white cross-site in the center of this picture (Fig. 23). The ROVNAV transducer carried by the ROV was fitted just above this camera so its crosshairs were centered directly below the transducer, which provided the known location on the site. This camera served as the vehicle's datum.

Transponders can be moved due to local tide or current variations. Thus, at the beginning of each dive the ROV followed an exercise that recalibrated them. At the start of operations two metal plates, each 30cm square with a cross-painted on them, had been placed on the sea bottom to create south and north datum points. One was located 60m south of the site and the other 60m to the north. When the ROV arrived on the seabed at the beginning of each dive the local temperature and salinity were established from the sensors on the array.

After the water density, and therefore the speed that sound would travel through the water, was established the ROV would position its navigation camera directly over the target on the south datum. If the x,y,z co-ordinates of this position did not agree within a few centimeters with the data observed after calibration, then the array would be 'virtually shifted' in the x,y plane by software to fit again. The ROV would then transit to the north datum, 120m away, and set up again over this target. Any error now observed with scale or skew could thus be corrected by rotating or rescaling the calibration to fit. If these two datums were kept consistent, then recording locations on the wreck site between them maintained a high degree of accuracy.

During operations, the 98 Series Hewlett Packard Navigation computer ran two displays. The first was located at the surveyor's station and displayed time returns, standard deviation of fixes and a graphic display of the 'cocked hat' triangle formed by the array returns. The second monitor at the pilot's station displayed a graphical representation of the site, with a moving icon representing the ROV and any other features on the site that had been logged into the system. The representation of the site was updated from time to time from the logging database as the excavation progressed. The navigation computer accepted and processed information on gyro, pitch, roll and depth from the ROV's computer. The raw data was then corrected for pitch, roll and the orientation of the ROV. The positional data was stored at the navigation computer and passed on to the logging computer.

The logging computer accepted positional data and kept track of any other operational event related to artifacts, camera stills taken and videotapes running. All data was placed in a FoxBase database using in-house software utilized with minimum keystroke activity by the operator to avoid typo errors. Although the facility to enter individual comments was available, most events could be registered using a single function key. At the end of a dive session the database was backed up to a WORM drive (Write Once Read Many), an early form of CD.

During the excavation, events recorded included, but were not be limited to (Fig. 33):

- Artifact Observed: all positional data and videotape numbers recorded across line of the database.
- Artifact Identified: eg. jar, sherd, pottery, porcelain, coin, gold bar, wood, ballast, utensil, etc.
- Artifact Removed: all the above date plus an ID Inventory Number and ID Basket Number.
- Artifact Basket Placed: As above information, plus data on the partition number of the 4Plex container in which the basket was secured. Also the excursion number of the 4Plex.
- Positional and recording data were taken for the following events: dredging started, dredging stopped, video started, video paused, still taken 35mm, still taken 70mm, frame grab.

Two Schilling Titan manipulators were fitted to the ROV Merlin. One was a seven-function position feedback unit used for all delicate operations. The other was a Schilling Titan five-function unit utilized mainly for holding the sediment removal nozzles and for lifting artifacts already contained in baskets (Fig. 17). The seven-function unit was controllable by the operator in jaw grip pressure ranging from a few ounces to 45kg. The main arm could lift object weighing up to 226kg.

Perhaps the most resourceful modification custom-made by the Tortugas team was the attachment to the ROV of a small, 5cm-diameter bellows type suction cup (Figs. 19-21, 36-37). The suction delivered to this device

Fig. 19. An early limpet suction device developed for the Tortugas project being used to recover an olive jar.

Figs. 20-21. An evolved small limpet suction bellows device used to recover artifacts from the Tortugas shipwreck inspired from paper printing industry technology.

Fig. 22. Observation of Merlin excavating, using the ROV's vertical black and white still camera.

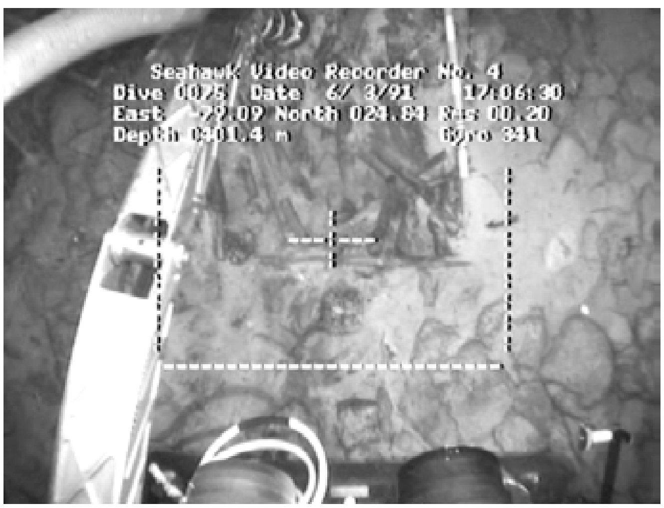

Fig. 23. Observation of Merlin excavating using the ROV's vertical black and white still camera, with its electronic grid position and geospatial data superimposed over the image. Similar data could be observed on all live and recorded video data.

was controllable by the operator. The cup could pick up the most delicate porcelain and olive jars without causing damage, yet could still remove large angular ballast stones. The invention and adoption of this limpet system on the Tortugas shipwreck went through several phases of on-site development and was the first application of this tool on a deep-sea archaeological excavation. The system is now a standard tool utilized by Odyssey Marine Exploration and other archaeological operatives.

Artifacts were initially secured in circular fishing baskets, which were numbered for input into the database and for recording onto videotape. They were fitted with 'jug' handles on the sides and 'bucket' handles on top to facilitate carrying by the ROV manipulator arms. The baskets were placed in sectioned off partitions in the large steel basket designed for retrieving artifacts from the sea bottom, nicknamed the 4Plex, which had a lifting capability of 3 tons (Fig. 24).

When the 4Plex was ready for recovery, a wire was lowered from the research vessel's recovery winch. Near the hook on this wire was a transponder that enabled the ship to reposition itself using its winches to guide the hook to within 50m of the 4Plex. When the hook arrived near the sea bottom the ROV approached it, grasped it with a manipulator and conveyed it to the 4Plex, where it could be hooked on and lifted to the ship (Figs. 25-30).

After recovery, an empty 4Plex would be sent down again with a transponder on the wire. The transponder relayed depth, thus permitting its descent to be halted just above the seabed. The ROV then pushed the 4Plex to the appropriate position before it was lowered completely onto the seabed. Merlin finally unhooked the wire from the 4Plex to allow the empty wire to be winched back to the surface. Due to the careful navigation of the ROV using the positioning system, at no time during the excavation were any entanglement problems encountered between the ROV umbilical and the 4Plex lift wire during deployment or recovery operations.

The sediment removal and filtration (SeRF) system used on the Tortugas excavation was a 25hp hydraulically-driven three-stage water pump (Figs. 17-18). This venturi pulled water and unobserved small finds through the main system (Fig. 36). No artifacts passed through any mechanical portion of the pump, so there was no damage to cultural remains that might have traversed the system. In addition to working sensitively around archaeological remains, this system could extract solid clay at full power. It could also be reversed to back flush the system or blow away silt and sand.

Many methods were tried and tested to filter sediment that might contain small finds unnoticed during excavation. Any form of screen or filter inserted into the venturi soon blocked up and curtailed the dive. A successful method was subsequently evolved based on the principle of a fuel filter using a container on which liquid is dropped from the top onto a domed plate. Solid objects fall to the bottom of the vessel beneath the domed plate. Excess water and fine silt was then discharged at the top, where it was ejected through a 2m-high stack.

A ram-operated, three-way select gate valve was utilized to select between usage of the main dredge nozzle and the suction limpet used for lifting artifacts. The venturi used was a 'Banjo' type, which ejected water through a ring. The aperture in the center, 9.0cm diameter, passed the

Fig. 24. An olive jar being secured into a 4Plex unit by the ROV Merlin using its limpet suction device.

Figs. 25-26. Artifacts secured in a 4Plex unit being winched onto the deck of the Seahawk Retriever. *Photos: John Astley.*

induced flow through the dredge nozzle. The main water pump relied on was a three-stage turbine, which required about 80 liter/min at 200 bar. The dredge nozzle and lifting suction limpet were stowed on hooks positioned near the Schilling Titan manipulator. The SeRF system nozzle measured 10.2cm in diameter and was attached by a flexible tube. The lifting limpet was adapted to a self-coiling airline hose.

The dredge receiver into which spoil was filtered was constructed from two 18 US gallon stainless steel pressure beer barrels built onto the rear of the ROV Merlin (Figs. 9-11). Its content size was suitable for dredging a cubic meter of clay (about one ton). When full the receiver typically held about 25% clay and 25% hard objects (stones, shell and small finds including pearls, seeds, coins, beads, glass, and human and animal teeth: Figs. 31-32). Simultaneously, nearly a ton of clay had exited via the three exhaust stacks in the form of fine debris that drifted away from site and created no visibility issues.

The size of the domed plate proved to be critical and was determined by trial and error. If the dome was too small it allowed too much turbulence in the bottom of the receiver. It was discovered that the best results were obtained by cutting the domed plate a little on the large side so that some clay was retained alongside any artifacts collected. The clearance between the edge of the dome and the receiver rim was 2.5cm. This served to protect and cushion the small artifacts, but demanded more intensive sorting after ROV recovery.

The SeRF system was attached to the stern of the ROV Merlin and could only be removed at the surface. In practice a bottom working time of about three to four hours proved feasible before the SeRF unit was full and had to be recovered.

Figs. 27-28. Numbered 4Plex units were recovered with a closed lid protecting the artifacts. Photos: John Astley.

Figs. 29-30. Archaeology team members examining the finds freshly recovered from the Tortugas shipwreck. Photos: John Astley.

Figs. 31-32. Archaeologist David Moore examines sieved spoil recovered from within the ROV Merlin's SeRF (Sediment Removal and Filtration System) unit. Photo (Fig. 31): John Astley.

PAGE NO. 7
06/17/91

REPORT OF ROV DIVING
.Seahawk Deep Ocean Technology,Inc. Dive Number: 84
.Ship: Seahawk Retriever Dive Date: Jun 16, 1991.
.ROV: Merlin Data File: D84-91.dbf .

TIME hr:mm:ss	EVENTNAME	COMMENT	EAST	NORTH	DEPTH (m)	RMS	GYRO
18:23:45	Artifact Removed # 1822	sherd	210.56	-95.31	403.26	34.27	48
18:23:56	Artifact Placed # 1822	basket 12	210.38	-95.32	403.26	34.26	48
18:24:50	Artifact Removed # 1823	sherd	210.47	-95.31	403.26	34.23	46
18:25: 1	Artifact Placed # 1823	basket 12	-80.53	16.89	403.00	0.08	45
18:29:46	Dredging End		-80.37	16.97	403.26	0.06	46
18:32:27	Stop VCR 1	Pause	-80.56	16.86	403.26	0.03	50
18:32:29	Stop VCR 2	Pause	-80.43	17.01	403.26	0.07	50
18:32:32	Stop VCR 3	Pause	-80.60	16.90	403.26	0.05	50
18:34:16	Start VCR 1	Continue	-80.52	17.19	403.00	0.04	50
18:34:18	Start VCR 2	Continue	-80.52	17.19	403.00	0.04	50
18:34:20	Start VCR 3	Continue	-80.43	17.03	403.26	0.13	51
18:34:25	Dredging Start		-80.43	17.03	403.26	0.13	50
18:39: 3	35mm Taken # 4	e.o.	-80.54	16.95	403.26	0.09	44
18:39:31	35mm Taken # 5	e.o.	-80.59	17.00	403.26	0.07	45
18:47:22	Dredging End		-80.50	16.94	403.26	0.16	45
18:48:45	Stop VCR 1	Pause	-80.59	16.98	403.26	0.07	44
18:48:50	Stop VCR 2	Pause	-80.62	17.01	403.26	0.14	50
18:48:56	Stop VCR 3	Pause	-80.55	17.02	403.26	0.10	49
18:49: 5	Dredging End		-80.55	17.08	403.26	0.07	49
18:49:21	Artifact Removed # 1824	sherd	-80.58	16.99	403.26	0.07	48
18:49:34	Artifact Placed # 1824	basket 12	-80.59	17.10	403.00	0.11	49
18:53:59	Start VCR 1	Continue	-80.64	17.05	403.26	0.05	49
18:54: 2	Start VCR 2	Continue	40.83	265.72	403.26	23.10	50
18:54: 5	Start VCR 3	Continue	40.83	265.72	403.26	23.10	51
18:54:12	Nav. Fix	close up video of large E.O.	-80.56	17.15	403.26	0.00	50
18:57:44	Stop VCR 1	Pause	-80.44	16.90	403.26	0.04	50
18:57:47	Stop VCR 2	Pause	-80.52	16.90	403.26	0.09	50
18:57:49	Stop VCR 3	Pause	-80.52	16.90	403.26	0.09	49
19: 9: 4	Start VCR 1	Continue	-81.39	15.86	403.26	0.09	54
19: 9: 9	Start VCR 2	Continue	-81.49	15.61	403.00	0.16	55
19: 9:10	Start VCR 3	Continue	-81.49	15.61	403.00	0.16	55
19: 9:24	Dredging Start	Continue	-81.29	15.64	403.26	0.12	55
19:15:23	Artifact Removed # 1825	sherd	-81.32	15.56	403.26	0.04	51
19:15:38	Artifact Placed # 1825	basket 12	-81.32	15.56	403.26	0.17	50
19:23:12	Dredging End	port	-81.30	15.67	403.26	0.15	54
19:24:32	Stop VCR 1	Pause	-81.58	16.12	403.26	0.08	39
19:24:35	Stop VCR 2	Pause	-81.66	16.25	403.26	0.09	38
19:24:39	Stop VCR 3	Pause	-81.66	16.25	403.26	0.09	39
19:28: 8	Dredging Start	port into aft reciever	-80.74	17.18	403.26	0.10	336
19:28:37	Start VCR 1	Continue	-80.85	16.99	403.26	0.09	335
19:28:41	Start VCR 2	Continue	-80.66	17.10	403.26	0.14	334
19:28:44	Start VCR 3	Continue	-80.74	16.99	403.26	0.17	334
19:37:57	Nav. Fix	backflush to basket 12	-80.73	17.08	403.26	0.12	334
19:41:17	Artifact Removed # 1826	wood frag	-80.68	17.20	403.26	0.09	336
19:41:31	Artifact Placed # 1826	basket 12	-80.70	17.01	403.00	0.23	336
19:44:36	Artifact Removed # 1827	sherd	-80.66	17.21	403.26	0.08	336
19:44:52	Artifact Placed # 1827	basket 12	-80.59	17.24	403.26	0.14	335

Fig. 33. Typical dive sheet maintained during the 1991 Tortugas shipwreck excavation.

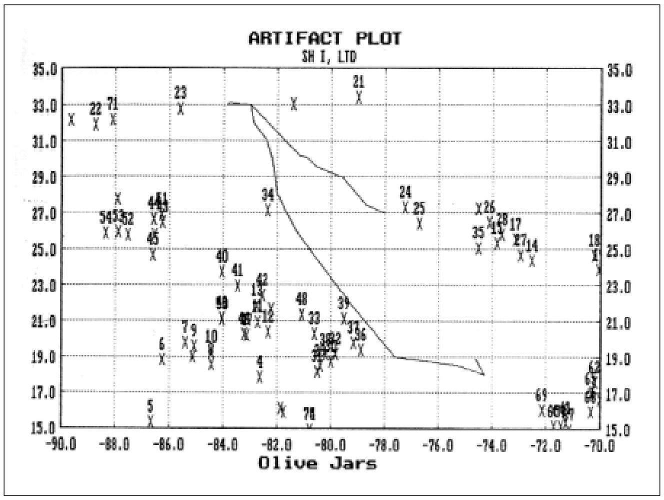

Fig. 34. An example of an original computer generated artifact plot from the Tortugas shipwreck excavation, in this case showing the positions of olive jars.

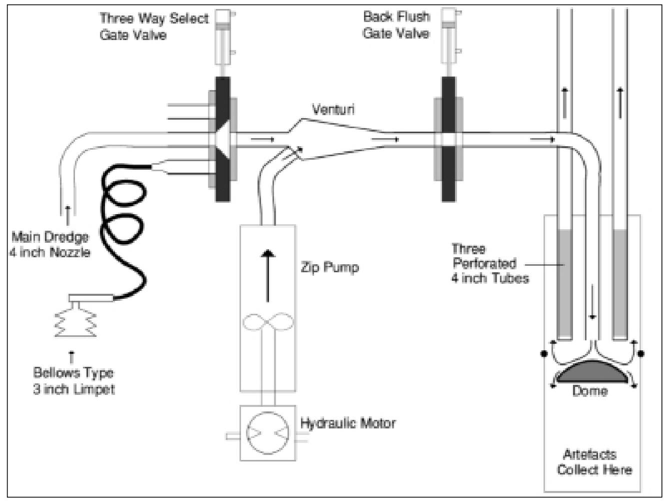

Fig. 36. A schematic diagram of the construction and operation of the venturi SeRF system developed for ROV Merlin for the Tortugas shipwreck excavation. Drawing: John Astley.

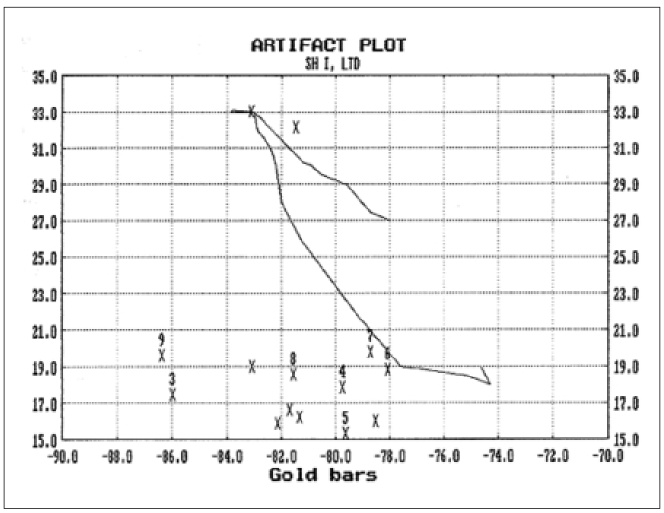

Fig. 35. An example of an original computer generated artifact plot from the Tortugas shipwreck excavation, in this case showing the positions of gold bars.

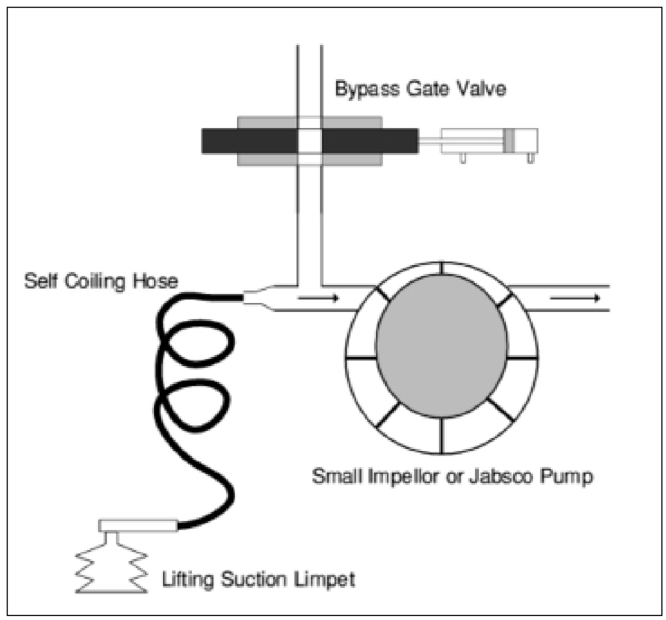

Fig. 37. A schematic plan of the limpet suction device developed for the Tortugas shipwreck excavation. Drawing: John Astley.

5. Excavation

Using the Long baseline navigational system already decribed, the position of Merlin was recorded every five seconds. Along with various vehicle orientation information received from Merlin's computers, this data was passed to a computer system developed by Todd Robinson of Seahawk Deep Ocean Technology to manage artifact provenience. Called the 'On Line Data Storage and Logging System', this system was run by the third member of the pilot crew, designated the 'datalogger'.

The system first took the received information, processed it and sent it to the display system that overlaid the data onto the video recorders. As activities unfolded on site, the datalogger entered appropriate comments and assigned artifact numbers to items as they were first seen, photographed and prepared for storage and recovery. That information was recorded immediately onto a paper log transcript and to an electronic database for further review by the team archaeologist. The paper log included a heading with Dive Number and Date and a continuous log of Time in hours, minutes, and seconds, followed by the Event Type, Comment, then the Position Coordinates.

The electronic database, stored on computer disc, could be accessed through a variety of methods. For example, a category of artifacts (ie. olive jars) could be imposed on an outline of the site so that the distribution could be studied. Any combination of categories could be plotted together showing their distribution over the site and contextual relationships. The computer could also be commanded to generate a plot (either on screen or paper) showing the distribution of the gold bars, glazed ceramic bowls or astrolabes, for example (Figs. 34-35). These plots proved invaluable in determining relationships between artifacts and site contexts during the course of the excavation – and then to recreate the site through post-processing after the project was completed.

During the excavation of the site the project archaeologist directed all activities undertaken by the ROV technicians. One of the key benefits of this remote system, as opposed to archaeological excavations by divers, was the ability of the entire team to view, discuss and contemplate the excavation strategy. This unique ability to share ideas during the course of the excavation was exceptionally useful when nearly every activity on the site required the development of new techniques and tools. The fact that every second of the excavation was recorded on video allowed thorough review and documentation of the project two decades after the excavation took place.

After ten months of excavation, thorough documentation of the site and recovery of just under 17,000 artifacts, the Seahawk team proved that it was possible to undertake a detailed archaeological excavation remotely using robotics, something never before accomplished. More than just allowing a primitive excavation, as one would expect from the inaugural attempt at such a complex task, the systems designed and utilized on this project provided a level of repeatable accuracy, artifact recovery and efficiency of recording that would serve to provide a model for the evolution of robotic excavation in the deep ocean for future generations.

Appendix 1: Scorpio 2000 ROV, 'Merlin'

Specification
- L. 2.4m.
- W. 1.85m.
- H. 2.5m.
- Weight (in air): 3,300kg.
- Payload: 150kg.
- Depth rating: 1,000 msw.
- Through frame lift: 3,000kg.

Hydraulic Power Unit
- HPU voltage: 3000 volts.
- Maximum current: 23 amps.
- HPU shaft power: 75 kW.
- Maximum flow: 190 1/min (50 US gpm).
- Supply pressure: 204 bar (3000 psi).
- Over ambient compensation pressure: 1.0 bar (14.7 psi).

Axial Thrusters
- Number: 2.
- Manufacturer: Innerspace.
- Type: 1002.
- Motor Type: RHL A70.

Vertical Thrusters
- Number: 4.
- Manufacturer: Innerspace.
- Type: 1002.
- Motor Type: RHL A70.

Bollard Pull
- Forward: 408 kgf (900 lbsf).
- Aft: 340 kgf (750 lbsf).
- Lateral: 408 kgf (900 lbsf).
- Vertical: 649 kgf (1430 lbsf).

Valve Packs
- One 12-station solenoid valve pack.
- One eight-station proportional valve pack.

Optics & Lighting
- Provision for five cameras with separate focus or zoom and on/off controls.
- Provision for one two-channel fiber-optic video multiplexer.
- Six 115-volt ac lighting power supply circuits at 250W each.

Sensors/Indicators
- Depth Digiquartz sensor.
- Heading gyro compass updated by fluxgate sensor.
- Pitch and roll sensor.
- Hydraulic pressure.
- Hydraulic temperature.
- HPU temperature.
- Water ingress.
- Pod temperature.
- Tether turns.

- ROV multiplexor status.
- Status of each analogue and digital signal.
- Analogue and digital signals to offset and span set from control console.

ROV Control
- Manual horizontal and vertical joystick control.
- Trim pot control.
- Full/half auto heading with trim pot offset.
- Manual pitch control.
- Manual roll control.
- Full/half auto altitude with trim pot control.

Additional Equipment
- Schilling 'Titan' seven-function manipulator with position feedback.
- Schilling five-function manipulator.
- Simrad Sonar system with 600khz.
- One Photosea TV1200 3 chip CCD TV Camera with 10:1 zoom.
- Two CCD colour fixed TV cameras.
- One OE1323 SIT TV camera.
- One OE1356 B+W TV camera.
- One Photosea 1000 35mm still camera.
- One Photosea 1500 strobe.
- Two Photosea 2000 70mm still cameras.

Umbilical
- Triple wire armored main lift umbilical.
- L. 1,000m.
- Two twisted screened quad.
- Two optical fibers.
- 12 3,000v rated conductors.
- Three 120v rated conductors.
- Four coaxial RG59 conductors.
- One safety shield/screen.
- Weight in air: 2,240 kg/km.
- Theoretical breaking strain: 15,260kg.
- Minimum bend radius: 75cm.

Appendix 2: Ship-Based & Navigational Specification

Control Shack
- External L. 6.1m.
- External W. 2.44m.
- External H. 2.72m.
- Air conditioned.
- Control Console.
- Three 30in Barcho monitors.
- Five 14in TV for video monitoring.
- One 14in vehicle position monitor.
- One 17in sonar monitor.
- One 17in site navigation monitor.
- Four Sony SVHS video recorders.
- One video switching matrix.
- One video overlay system.
- One data recorder computer and monitor.
- One navigation computer and PANS control unit.

Deck Equipment
- A Frame launch over the side from midship position.
- Umbilical winch: line pull 4,620kg.
- Generator: 440 volts (150 kva).
- Crane 1: 5-ton mounted near launch to assist if required.
- Crane 2: 5-ton mounted near stern to deploy moorings.
- Winch: 8-ton pull 800m cable to recover 4Plex.
- Two 4Plex recovery containers.
- Four 5-ton Bruce anchors.
- Four 3m-diameter mooring buoys.
- 122m of 8.9cm studlink chain to connect anchors.
- Four mooring winches, each 25-ton pull, loaded with 2km of 6.3cm wire.
- One two-drum waterfall winch, each 50-ton pull.

Research Ship
- Originally named the Tera Tide, a supply boat with all accommodation forward leaving a long low deck area, renamed the Seahawk Retriever.
- L. 64m.
- Beam 9.8m.
- Engines: 2 x V18 Alcho railroad engines. (These could provide the considerable power to deploy the anchors and drag out the suspended wire cables, but used 14 tons of fuel per day. Once anchored the engines were shut down for the season.)
- Propellers: 2 x 305cm variable pitch.
- Accommodation: modified for 15 people.

Navigation
- Four Sonardyne compact transponders, with depth, temperature and salinity sensors.
- One Sonardyne compact transponder with ability to interrogate, receive and relay data from bottom array to the ship.
- One Sonardyne ROVNAV system.
- One Sonardyne PANS system.
- Interrogation rate 1,500ms.
- All transponders set to operate between 28 and 32 khz.