An ASV for Coastal Underwater Archaeology: the Pladypos survey of Caesarea Maritima, Israel

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***Abstract*—Coastal underwater archaeological sites are by nature dynamic, and often subject to disturbance from the action of waves, currents, sediment, and human activity. The need to document such sites comprehensively, accurately, and quickly has been the driving force behind technological advances in pre-disturbance site mapping since the 1960s. Certain challenges remain constant: the need for technology to be affordable and robust, with efficient post-processing as well as data acquisition times. Non-engineers must be able to interpret the results and publish them according to archaeological conventions. Large ancient shallow water port sites, submerged settlements, and landscape surveys present additional difficulties because of the volume of data generated. In this paper we present initial results of the first season of an expedition to map the submerged Herodian structures at Caesarea Maritima, Israel, using a robotic vehicle, the Autonomous Surface Vehicle (ASV) Pladypos, which was developed to address these challenges. This vehicle carries high-resolution imaging and remote-sensing tools to produce photomosaics and microbathymetry maps of the seafloor, as well as performing precise georeferencing. The Pladypos acquired a vast amount of georeferenced bathymetric and photographic data over several days in May 2014 and the results were later integrated into a GIS.**

I. INTRODUCTION

Since the early years of the modern discipline, nothing in underwater archaeology has evolved as dramatically the technology of site and landscape recording. Photogrammetry, Photo-modelling, SLAM, structured light imaging, multibeam and various other acoustic sensing technologies have all been utilized on Mediterranean underwater sites in recent years [1] [2] [3] [4]. Yet as much as archaeologists are eager to trade the laborious work of manual recording for more efficient methods, no single technology has demonstrated enough clear advantages for it to be widely adopted or accepted as the new standard for digital site recording. Issues of cost, accuracy, reliability, and post-processing time are usually paramount. The ability to integrate DVL point clouds and photomosaics to produce archaeologically useful diagrams and publication-quality maps is also a concern for archaeologists who typically lack the training to process the data themselves. In addition, advances in oceanographic mapping are often developed with deep water in mind, while the shallow environments where archaeological material is concentrated demand different, low-cost solutions.

In a shallow water, marine robotics is emerging as a promising field offering a wide range of possibilities for pre-disturbance survey (2.5D site or landscape recording without excavation) [5]. In these coastal underwater archaeological scenarios, marine robots are not faced with the technical difficulty of operations in deep water, but arguably face a far greater challenge in that they are entering direct competition with human divers. Archaeologist scuba divers, often student volunteers, combine high mobility, intelligent navigation, and an enormous range of manual capabilities for a minimal operational cost. These human advantages start to disappear, however, as the area to be surveyed gets larger or deeper, or the time available for field operations becomes shorter. These are the scenarios in which the advantage of robotic vehicles with the ability to take thousands of instant measurements and photos along precisely georeferenced survey lines becomes clear.

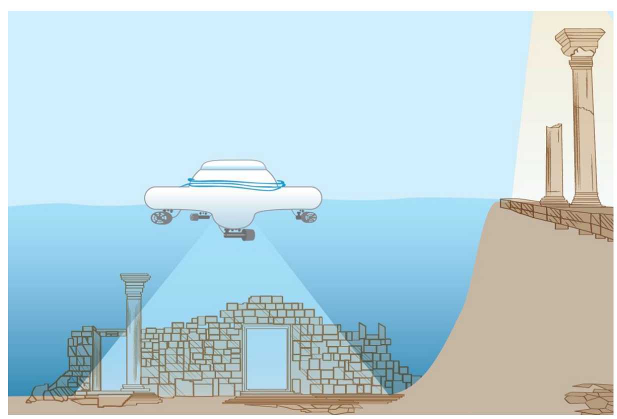

Fig. 1: Illustration of the ASV Pladypos mapping system.

Navigation and localization are among the most difficult problems in underwater vehicle development, but these problems can be avoided in shallow coastal underwater archaeology by the use of surface vehicles relying on a combination of GPS and DVL navigation. A surface vehicle also offers a fast wireless communication link with the base, unlike the slow acoustic communication channel required underwater. Fig. 1 illustrates the ASV Pladypos, an autonomous PLAtform for DYnamic POSitioning that utilizes these advantages in a new

(a) Surface (b) Underwater

Fig. 2: The Pladypos operating at sea from two perspectives.

approach to submerged coastal landscape archaeology. The Pladypos is a highly maneuverable ASV that can deploy with a variety of payloads for seafloor imaging and remote-sensing within conventional scuba-diving depths. In 2014 field tests in Israel, we tasked the Pladypos with collecting data for a complete georeferenced archaeological site map of Caesarea Maritima, an operation that could have taken years to complete with human divers.

II. CAESAREA MARITIMA

A. Historic overview

"By dint of expenditure and enterprise, the King triumphed over nature and constructed a harbor larger than the Piraeus. Notwithstanding the totally recalcitrant nature of the site, he grappled with the difficulties so successfully, that the solidity of his masonry defied the sea, while its beauty was such as if no obstacle had existed. The city Herod dedicated to the province, the harbor to navigators in these waters, to Caesar the glory of this new foundation, to which he accordingly gave the name of Caesarea."

Josephus, *Jewish War* I.410-412, text adapted from the translation of [6].

As the first century Jewish writer Josephus observed, the construction of Caesarea Maritima was a grand gesture in keeping with the ambition of its king, Herod I of Judaea, and the power of his patron, the Roman emperor Caesar Augustus. The name Caesarea came from the family name of Caesars; Sebastos, the harbor's special name is the Greek rendering of Augustos. The new city's most notable feature was a large artificial harbour encompassing an area over 200,000 square meters [7]. Upon its completion in the last decade of the first century BCE, Caesarea's port provided the eastern Mediterranean's only deepwater anchorage between Dora (Tel Dor) in the North and Joppa (Jaffa) in the South. The "triumph over nature" described by Josephus included massive artificial breakwaters built up from the seafloor using hydraulic cement foundations consisted of a mass of aggregate, or stone rubble bonded by means of special mortar composed of lime and pozzolana, volcanic ash from central Italy. Colossal statues and towers rose up along Caesarea's wharves and quays, and the city itself grew to be five times the size of Jerusalem. It remained the most important port in the province until the Muslim conquest.

The artificial harbour that began as one king's vision continued to develop over the centuries, until at last the forces of nature overtook human efforts to preserve it. Today Caesarea's ruins are the centerpiece of a national park adjacent to the modern town of Qesarya. The sunken foundations of the breakwaters and quays described by Josephus are buried in sand and scattered afar, presenting a challenging puzzle for archaeologists trying to reconstruct Herod's original plan. After winter storm seas in 2010 were powerful enough to tear down even Caesarea's modern reinforced-concrete breakwaters, the need for a new conservation assessment of the ancient harbor became clear. Completing the first comprehensive survey and GIS of the entire underwater site will aid in future planning, and also serve as a means of integrating the results of decades of smaller-scale recording efforts.

B. Present archaeological work

The first systematic archaeological work in Caesarea's port took place in the 1960s with the expedition of Edwin and Marion Link, and continued for many years under the direction of pioneering Israeli underwater archaeologist Avner Raban [8]. A series of prominent archaeologists and organizations have at times led the research in collaboration with the Israel Antiquities Authority: the Caesarea Ancient Harbor Excavation Project (CAHEP), Combined Caesarea Explorations (CCE), and more recently, the Caesarea Coastal Archaeology Project (CCAP), to name a few. The Roman Maritime Concrete Study or ROMACONS project also increased our understanding of Caesarea by analyzing the methods of underwater construction used at the site. Each expedition brought with it new recording technologies and techniques. However, Herod's harbour is a dynamic and sometimes violent place. Strong seas, low visibility, shifting sand, concretion, erosion, and the gradual merging of natural and man-made features over the past two millennia all complicate the already-ambitious task of mapping one of the Mediterranean's largest ancient ports.

The underwater mapping of Caesarea understandably began in a piecemeal fashion. While much detailed manual recording took place in specific areas, the overall site plan remains to this day an imprecise schematic of the visible surface features as seen from aerial photography. The adoption of digital trilateration and PhotoModeler software for recording underwater sites in the 1990s led to the first computer-generated models of Caesarea's submerged ruins. These original point-cloud maps, while effective for delineating ancient amphora wrecks, were less successful at Caesarea, where many of the sunken architectural features are now eroded and concreted into amorphous lumps [9].

More recently, three newer technologies have been applied at Caesarea with mixed but nevertheless significant results: multibeam, subbottom profiling, and magnetic survey [10]. The promise of the latter two technologies is their ability to record features below the highly disturbed surface of the visible site, which is essential to understanding the original structures. As these three technologies continue to evolve to provide greater precision, more accurate localization, and less

Fig. 3: The Pladypos holding position along a survey transect despite large waves.

onerous post-processing, they will no doubt be used again at Caesarea. At the time of writing, however, our map of Herod's port is at best an incomplete patchwork. There has been no effective large-scale integration of the available bathymetric, archaeological, and sub-surface data with information from excavations and coring over the last 60 years. Moreover, the movement of sea and sand is constantly transforming the visible site, and any recording strategies must take this into account.

The current environmental threats facing Caesarea Maritima along with many unanswered historical questions require a new approach to mapping Herod's harbour. Unlike the archaeologists of the previous century, we can now integrate a vast amount of georeferenced bathymetric and photographic data into a GIS, so that we are no longer forced to choose between coverage and accuracy in underwater recording. Until recently, however, there has not been an appropriate vehicle for conducting such a large-scale systematic underwater survey at Caesarea with the appropriate level of precision.

In summer 2014, the autonomous surface vehicle Pladypos began the first merged multibeam and photographic imaging of the sunken port structures. The goal of this ongoing project is to create the first full-scale fully-georeferenced underwater site map of Caesarea with a level of accuracy and detail normally only seen in small-scale underwater excavations.

III. RESOURCES

The ASV platform PlaDyPos [11] was developed at the University of Zagreb Faculty of Electrical Engineering and Computing, at the Laboratory for Underwater Systems and Technologies (LABUST). In May 2014, the Pladypos was brought to Caesarea to begin collecting data for the first merged multibeam and photographic imaging of Herod's entire harbor complex. The Pladypos is over-actuated with 4 thrusters forming an X configuration. This configuration enables motion in the horizontal plane in any direction. The current version of the platform is 0.35 meters high, 0.707 meters wide and long, and it weighs approximately 25kg, without payload. This lightweight design allows the ASV to be easily deployed by two people from a beach or jetty. In line with the need for swift data-gathering in response to Israel's winter storms that often temporarily remove meters of covering sediment from inshore archaeological sites, the vehicle was also designed to be quick to program for a desired mission. These features eliminate the labor-intensive mission planning, cranes, winches, and research vessels that typically support the operation of larger marine robotic vehicles, making the Pladypos ideal for investigation and monitoring tasks where fast response times and mission flexibility are important.

The vehicle has a ROS based architecture (http://www.ros.org) for control, communication, telemetry, and acoustic and optical data logging. The navigation sensors provide a level of localization accuracy within tens of centimeters and consist of 9-axis INS, high precision GPS, and Doppler velocity logger (DVL). The 4-beam DVL (LinkQuest 600) is capable of 5Hz depth sampling in shallow water, and generates a point cloud at the rate of 20 points per second. At a cruising speed of 1 knot, the DVL produces a non-homogeneous point cloud density of 40 points per square meter. For documenting an underwater archaeological landscape extending over several square kilometers, this represents extremely detailed coverage, though improving the point cloud resolution continues to be a goal for future development of the vehicle.

IV. EXPERIMENTS AND RESULTS

The Pladypos field experiments were conducted in Israel from 18th to 22nd of May 2014 and focused sections of both the inner and outer Herodian harbors at Caesarea Maritima. The foundations of a Roman pier were also mapped at nearby Sdot Yam to the south. One of the Herodian harbor survey areas is depicted in fig. 3. The vehicle was launched and recovered from Caesarea's modern breakwater. When sea conditions allowed it, the Pladypos operated along the southern breakwater of the outer Herodian harbor, where the water depth and reasonable seafloor visibility extends down to 8 meters. When the open sea became too rough, the Pladypos surveyed the ruins of a Roman and Crusader towers in the more sheltered area of the inner harbor, which ranges in depth from 1-3 meters. Since the Pladypos can be operated either manually (teleoperation mode) or autonomously, it was possible to adapt pre-planned missions in progress to respond immediately to changing sea conditions, water traffic, and other factors.

During the trials at Caesarea Maritima, two types of data were collected: a georeferenced point cloud of the seabed and archaeological features using the DVL, and visual imaging using a low light mono camera, the Bosch FLEXIDOME IP starlight 7000 VR, in a custom-made waterproof housing. A GoPro Hero3 camera in a waterproof housing was also taped on to the vehicle for several missions to gather additional video. The georeferenced point cloud was acquired by performing pre-programmed lawn mower missions across the site area. This data was processed off-line to create a

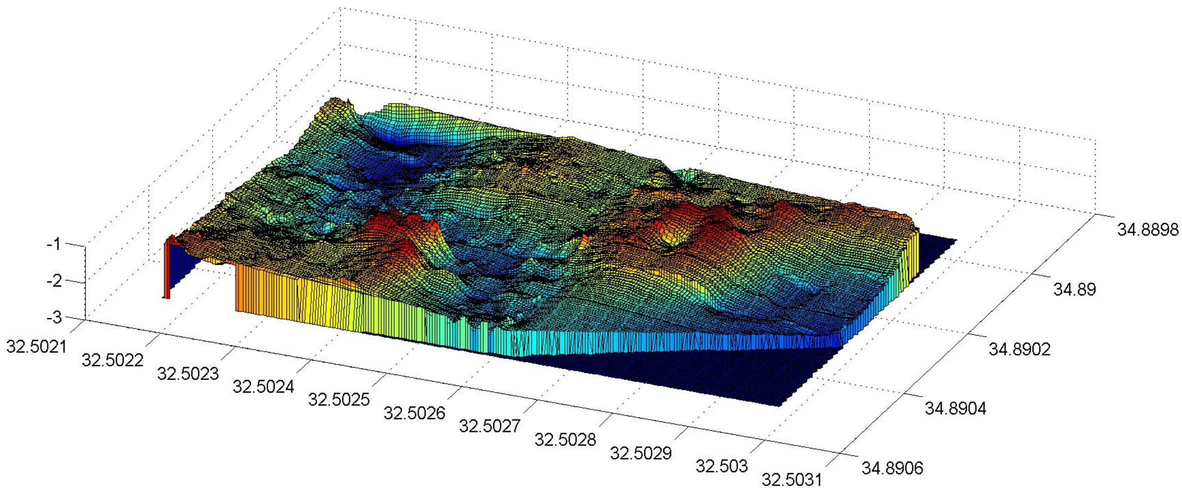

Fig. 4: 2.5D visualization of a Roman and Crusader towers foundations at Caesarea.

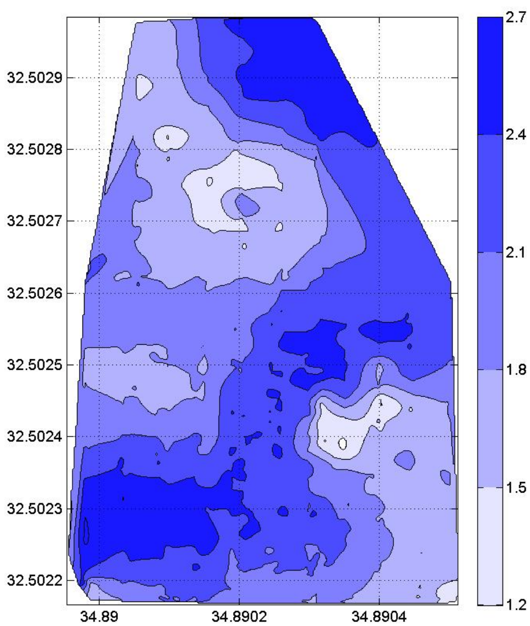

Fig. 5: Partial bathymetry map of Caesarea's inner harbor, showing the foundations of a round Roman and square Crusader tower.

microbathymetry map, and a 2.5D digital model of the scanned seabed was also extracted and created from the same data set. The optical data was then merged with the telemetry data to build photo mosaics of the scanned transects. Preliminary mosaics were produced on site at the land station, providing high resolution images and real-time information to the archaeologists in the field.

The first mission performed by the Pladypos in Caesarea's inner harbor was a survey of the foundations of a round Roman tower and square Crusader tower. Like many of Caesarea's structures, these semi-buried ruins are not immediately obvious or comprehensible to a swimmer seeing them close-up underwater, where perspective is limited. However, the sand and rubble transform into recognizable architecture when reconstructed as a 2.5D digital image (fig. 4). The georeferenced microbathymetric map of this area illustrated in fig. 5 was created using customized Matlab-based software developed by LABUST. The results are suitable for GIS presentation, for example using Google Earth as shown in fig. 6.

Herod's outer harbor was more exposed and deeper, with the depth range of 3-8 meters in the area surveyed. Despite windy conditions, the Pladypos held position and continued to collect good data even in slightly choppy seas, a steady 1-1.5 knot current, and Caesarea's infamous surge. Three missions were performed along a 250 meters stretch of the submerged southern breakwater, and the results were merged to create a 2.5D reconstruction (fig. 8) and a microbathymetry map (fig. 7). Optical data were used to produce a photomosaic of the surveyed area off-line. For image stitching we have tested freely available software such as Microsoft ICE as well as applications developed in-house at LABUST. Image stitching software uses only the optical data, and the mosaics created must be aligned with the telemetry data in subsequent processing. LABUST has developed software to fuse optical and telemetry data for both image stitching and georeferencing. On the final large-scale "photographic quality" site map produced from this process, information such as the absolute positions of underwater objects and features and their dimensions can be determined within a range of centimeters.

Fig. 10a shows a photomosaic of one of the mission transects in a GIS overlay (Google Earth). The level of detail is illustrated in fig. 10b, which depicts a close up of the area outlined by the white square in fig. 10a. On dynamic coastal archaeological sites where the visible remains are often changing, being able to study the relationship between submerged and semi-submerged archaeological features and land-based features is very important. GIS visualization of the data with satellite or orthophoto [12] imagery of the surrounding area,

Fig. 6: Google Earth image of Caesarea's inner harbor with an overlaid bathymetry map.

as illustrated in fig. 6 where the data is presented on Google Earth, is an extremely useful tool. Observing change over time in both the land and underwater landscapes can help both archaeologists and local authorities to monitor coastal erosion and other long-term changes that threaten the archaeological site.

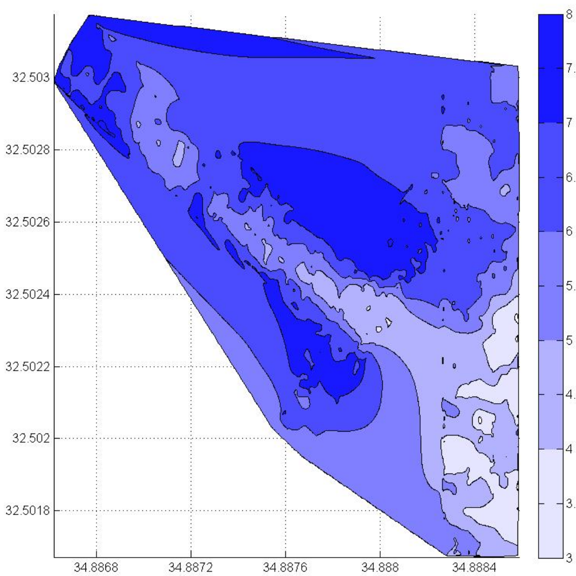

Fig. 7: Partial bathymetry map of the southern breakwater in Caesarea's outer harbor.

V. FUTURE DEVELOPMENTS

The recent development of DVL systems compact enough for deployment on small ASVs such as the Pladypos create important new opportunities for the recording and monitoring of large shallow-water coastal archaeological landscapes. On smaller sites, such as single structures or shipwrecks, recording the dimensions of timbers and artefacts to sub-centimeter accuracy should be the goal. When the Pladypos returns to complete the mapping of Herod's harbor in 2015, it will be equipped with a high-resolution multibeam sonar to generate a higher point cloud density and even more detailed 2.5D site maps. Using these capabilities, we anticipate being able to meet and surpass the very high standards of accuracy in manual site mapping established by scuba divers in the late 20^{th} century. The goal is to make the Pladypos just as useful for the intensive recording demands of shallow water shipwreck excavation as it has been for large-scale archaeological landscape survey.

Fig. 8: Images stitched together using Microsoft ICE freeware. The next phase is the integration of georeferencing.

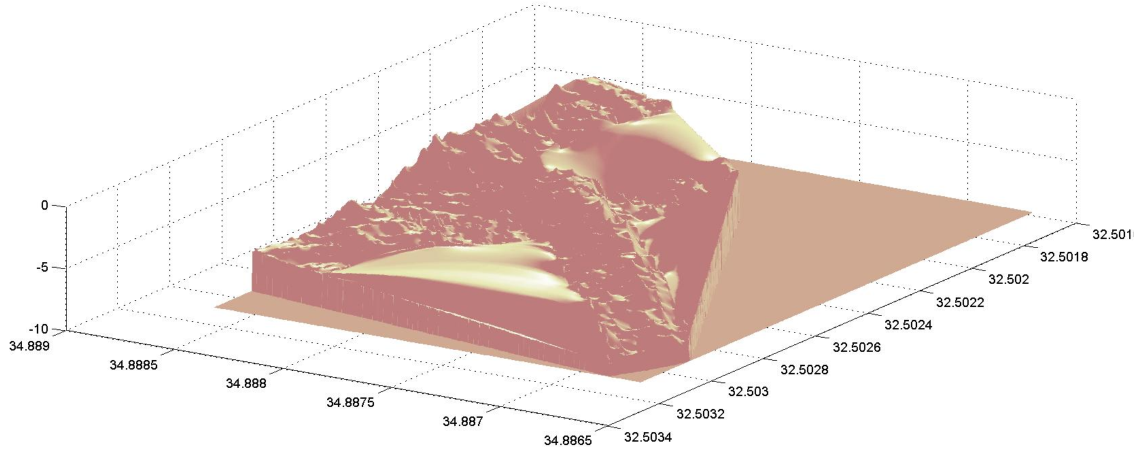

Fig. 9: Digital reconstruction of a 250 meters section of Herod's southern breakwater.

(a) Mosaic overlaid on Google Earth. mosaic

(b) Detail of the area enclosed by the white box in (a). frame

Fig. 10: Photomosaic from Caesarea's inner harbor.

To this point we have been discussing operations in very shallow water, which may be defined as the depth at which the seafloor is still visible from the surface for the purpose of creating photomosaics. However, the utility of the Pladypos does not end there, and future missions will develop and demonstrate the vehicle's applications in deeper water. While it was stated above that the Pladypos' sphere of operations puts the vehicle into competition with human divers, it is more appropriate to say that the vehicle is designed to complement human capabilities. The Pladypos is designed to incorporate human functionality into its own to accomplish tasks in deeper water that would be expensive, difficult, or even impossible for the current generation of underwater robotic vehicles.

In the 2014 trials at Caesarea, the Pladypos joined scuba divers as a surface support vehicle for underwater archaeology (fig. 11). The Pladypos is equipped with an integrated ultra-short-baseline (USBL) localization system, which it uses to hover above and track a scuba diver with a tank-mounted transponder and battery pack [13]. The ASV is also equipped with an acoustic modem that maintains a low bandwidth link with the surface, allowing the transfer of email messages, photos, and GIS data between the diver and the land base via an ordinary PC tablet in a waterproof housing. The diver can access most of the tablet's applications using a touch-screen pen. While the archaeologist gathers data and images using the tablet, the Pladypos collects multibeam data and relays information to the diver about his or her location on the map, including transect lines and GPS coordinates. In this way, vehicle does not lose the ability to produce georeferenced photomosaics from the surface at depth or in poor visibility: it simply delegates part of the task to a human diver. The Pladypos is also being developed to enhance diver safety. The vehicle currently serves as a surface marker for the diver's position, which is very useful when manually checking sonar targets in offshore live-boating situations. In future, the Pladypos will also be able to monitor the divers physical state, duplicating the role of a human dive buddy as well as a scientific assistant.

VI. CONCLUSION

The immediate goal of this ongoing project is to create the first complete, detailed, and fully-georeferenced underwater

Fig. 11: Using a PC tablet to communicate with the Pladypos, archaeologists record the position of ancient ruins on a portable GIS of Herod's harbor. The ASV tracks and follows the divers from the surface.

site map of Caesarea Maritima using a combination of imaging and remote-sensing tools. This map will be used for research and to help manage the site. The over-arching goal is to develop through interdisciplinary collaboration the first universal standard robot customized for underwater archaeology, and to make it as versatile, robust, and affordable as possible.

Our May 2014 expedition demonstrated that when equipped with an appropriate payload, the ASV Pladypos was an efficient and effective tool for mapping a submerged coastal archaeological landscape. DVL altitude data generated a point cloud good enough for the production of local microbathymetry maps and 2.5D visualization of the seabed, while optical data was quickly processed into publication-quality, georeferenced photomosaics. The sea trials helped the engineering team to identify and address technical and application issues for future work, and experience first-hand a real archaeological mission environment. The mission itself helped to build mutual understanding of the needs of specialists in two very different fields, as well as improving their ability to communicate productively and work together towards common goals. We view the 2014 Caesarea expedition as an early step along a path to the full integration of robotic vehicles into all aspects of underwater archaeology. Such a major transformation will require further improvements in the technology, but the culture and methodologies of underwater archaeologists will also need to adapt. Collaborative field trials help to achieve both goals.

The next set of field trials in the same location is planned for July 2015. The future work will be focused on the integration of a low-range and high-resolution multi-beam sonar on the ASV for very detailed bathymetry and spatial modelling. The Pladypos will also be deployed on a variety of archaeological tasks that will contribute further to our understanding of Herod's famous harbor.

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