Journal of Archaeological Science 36 (2009) 2415–2426

Contents lists available at ScienceDirect

Journal of Archaeological Science

journal homepage: http://www.elsevier.com/locate/jas

A computerized system to determine the provenance of finds in archaeological sites using acoustic signals

A.R. Jiménez [a,*], J.C. Prieto [a], J.L. Ealo [a,b], J. Guevara [a], F. Seco [a]

[a] Instituto de Automática Industrial, Consejo Superior de Investigaciones Científicas – CSIC, Ctra. Campo Real km 0.2 La Poveda, 28500 Arganda del Rey, Madrid, Spain
[b] School of Mechanical Engineering, Universidad del Valle, Colombia

ARTICLE INFO

Article history:
Received 11 January 2008
Received in revised form
16 December 2008
Accepted 29 June 2009

Keywords:
On-site artifact provenance
Spatial localization
Computers in archaeological excavations

ABSTRACT

Some archaeological excavations require the accurate determination of the provenance of finds (three-dimensional location and orientation) for a subsequent spatial analysis. The traditional manual measurement using a grid reference is not a very efficient registration method. Some proposed computerized solutions based on total stations, photogrammetry and DGPS, are more effective but have some limitations. This paper presents a new acoustic localization system (3D-LOCUS) for measuring the three-dimensional position of finds in archaeological sites. The system can also be used for registering the size, shape and orientation of artifacts. 3D-LOCUS basically consists of a set of wireless rod-like pointing devices that are localized with a network of intelligent nodes installed above the excavation site. Archaeologists use the pointing device as a stylus to locate and outline the object under study. The main technological characteristics of the system are: omnidirectional wideband acoustic transducers, Bidirectional Time-Of-Arrival (BTOA) estimation, redundant ranging and robust trilateration. 3D-LOCUS achieves an accurate registration, even if used simultaneously to the digging labor, or in noisy or turbulent airflow conditions. We tested the system in the *Gran Dolina* archaeological site (*Atapuerca*, Spain). The typical location accuracy is below 10 mm in natural conditions, and the achieved resolution is 5 mm, which allows us sketching objects with enough detail.

1. Introduction

During the last decades, computers have played an important role in archaeology, mainly through the use of databases and statistical tools (Doran and Hodson, 1975). Computerized systems have been proposed (Dibble and McPherron, 1988) to assist the different stages in archaeological field works: (1) computerized artifact data acquisition, (2) integration of different types of data into computer databases, and (3) data analysis and graphical manipulation. Current advances in information and communication technologies have now the potential to be used in creating new archaeological aids, for example, provenance tools for excavations requiring a high level of recorded detail.

Gran Dolina is one of those archaeological sites that requires a detailed artifact provenance registration. This includes the exact three-dimensional position, orientation and shape of every object uncovered. *Gran Dolina*, a worldwide-recognized site by the discovery of fossils from *Homo antecessor*, is one of the caves belonging to the *Atapuerca* archaeological complex (Fernández-Jalvo and Andrews, 1992). It is located in a region of karstic hills (1100 m high) in the north of Spain. In this site thousands of fossils are discovered every year needing to be accurately registered.

The current procedure to get the provenance of finds in *Atapuerca* is not satisfactory. *Gran Dolina* excavation site has a working area of 60 m^2 and an intensive digging activity (Fig. 1). Using strings, the excavation area is partitioned into reference cells of one square meter each for measuring the XY coordinates of finds; a levelled laser beam and a measuring rod are used for measuring their vertical coordinates. After each artifact is manually registered for position, orientation and size, the archaeologist writes this information in a PDA (Personal Digital Assistant), or alternatively in a notebook. The time needed for measurement and annotation is significant, and therefore, the digging speed is quite slow (at this pace, excavation works are foreseen to last for 30 years or more). In order to improve the registration process at *Atapuerca*, we have been looking for new methodologies to register artifacts faster, accurately and efficiently.

Some modern methodologies have been proposed for automated on-site artifact provenance registration, mainly: total stations,

* Corresponding author. Fax: +34 91 871 70 50.
E-mail address: arjimenez@iai.csic.es (A.R. Jiménez).
URL: http://www.iai.csic.es/lopsi

0305-4403/$ – see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jas.2009.06.027

Fig. 1. *Gran Dolina* excavation site in *Atapuerca* Archaeological complex, Burgos, Spain.

photogrammetry and Global Positioning Systems (GPS). Some publications describe how to use total stations for determining the 3D position of finds (Dibble, 1987). Also, it is explained by (McPherron, 2005) the procedure to obtain their spatial orientation. Short-range photogrammetry has been proposed for digitalizing archaeological sites as 3D models, and also for artifact's position estimation (Schindler et al., 2003; Tack et al., 2005). Many archaeological sites are now topographically digitized using sophisticated GPS receivers (Colosi et al., 2001; Wheatley and Gillings, 2002). Real Time Kinematics Differential GPS receivers (RTK-DGPS) are used because they have the potential to achieve subcentimeter positioning accuracy (Misra and Enge, 2006).

Above mentioned provenance methods (total stations, photogrammetry and GPS) are valid alternatives to the on-site object coordinate determination problem. In spite of the benefits offered by them, several important limitations still remain. Table 1 shows some of the main disadvantages, as well as advantages, of each registration method. These limitations cause that, even today, the most common practice to register the provenance of a find is still the traditional spatial partitioning and manual measurement method.

For non-archaeological applications, some alternative technologies have been developed for localizing objects in local spaces (Hightower and Borriello, 2001; Prieto et al., 2007). Some of these solutions, called Local Positioning Systems (LPS), could have the potential to be useful for provenance registration. Next section introduces research of interest in this field.

2. LPS for provenance registration

An LPS is a solution for estimating the position of objects in restricted areas. They are able to localize in those places where satellite-based GPS cannot (e.g. indoors). An LPS consists of a network of fixed nodes acting as beacons at known positions, and additional mobile nodes which positions must be estimated. The measurement of distances or angles, between a mobile node and some fixed beacons, is the basic information required to calculate the mobile node's position. Location can be estimated from ranges by lateration algorithms, or alternatively using angles and triangulation techniques.

Different sensing technologies and designs have been proposed for LPS: (1) light detection and vision (Want et al., 1992; Krumm et al., 2000), (2) ultrasound Time-Of-Arrival (TOA) or Time-

Table 1
Existing artifact provenance methods and indication of some of their advantages ⊕ and disadvantages ⊖.

Spatial site partitioning	⊕ Easy concept and low-cost
	⊕ Permanent installation (left overnight)
	⊖ Time consuming measurement process
	⊖ Subsequent data transfer to a computer
	⊖ Prone to occasional large errors
Total station	⊕ Accurate at mm level
	⊖ Sequential registration
	⊖ Collaboration of two persons
	⊖ Line-of-Sight to reflective prism
Photo-grammetry	⊕ Realistic images of the excavation
	⊖ Manual image matching postprocessing
	⊖ Artificial marks on every object
	⊖ Clear excavation area for registering
Differential RTK-GPS	⊕ Accurate at cm level
	⊖ Multipath effect
	⊖ Not operative in caves, trenches or valleys

Difference-Of-Arrival (TDOA) (Martín-Abreu et al., 2002; Balakrishnan and Priyantha, 2003; Hazas and Hopper, 2006; Jiménez and Seco, 2005; Prieto et al., 2009), (3) ranging with radio signals by measuring either the Time-of-Arrival (e.g. UWB, Pseudolites) (Fontana and Gunderson, 2002; Werb and Lanzl, 1998) or by using the Received Signal Strength (RSSI) (e.g. WiFi, Bluetooth, RFID) (Ni et al., 2004; Bahl and Padmanabhan, 2000; Koutsou et al., 2007). These proposed LPS solutions are mainly devoted to applications such as robotic guidance and person position monitoring. The obtained accuracy and coverage varies from a few centimeters to several meters.

Radio-based LPS have in general a very limited accuracy. Radio LPS solutions that are based on the indirect estimation of ranges through RSSI, are only accurate at meter level (Koutsou et al., 2007). Using UWB radio-LPS technology, an accuracy of 20–30 cm is expected (Fontana and Gunderson, 2002). Ranging with radio signals in confined spaces is difficult. Strong multi-path propagation causes interference and signal dispersion, making difficult a reliable detection and TOA estimation. On the contrary, sonic signals can be more accurately processed for TOA estimation, since the propagation speed of sound is one million times slower than radio and multipath is only restricted to specular reflections in near-by objects. Positioning errors with ultrasonic LPS are in the order of centimeters in indoor conditions (Martín-Abreu et al., 2002; Balakrishnan and Priyantha, 2003; Hazas and Hopper, 2006; Jiménez and Seco, 2005; Prieto et al., 2008).

There do not exist ultrasonic LPS specifically designed for archaeology, except for a previous prototype by the authors (Jiménez and Seco, 2005). This LPS solution proposed the use of a long rod of 2 m length, as a measuring pointing device. These rods are equipped with two 40 kHz cylindrical emitters made of PVDF (Poly VinyliDene Fluoride). One emitter is positioned on the upper tip of the rod, and the other 70 cm below its top. Eight piezoelectric receivers are fixed on four posts in the excavation area defining a valid working area of 4×4 m. This configuration allows free-of-obstacle ultrasound propagation among nodes, avoiding the blockage of ultrasound signals by archaeologists digging in the excavation. A computer with an acquisition board captures the ultrasound signal coming at each receiver, measures TOA and performs the trilateration for rod's position estimation. As wind strongly influences the accuracy of estimated ranges, a differential compensation method was implemented. It uses an extra emitting reference node at a fixed position, as DGPS does, that diminishes location errors caused by airflows.

This first archaeological LPS prototype was promising since it demonstrated that it is possible to achieve sub-centimeter accuracy in ideal conditions using ultrasound technology. However, many limitations were found: (1) the differential air compensation method was not effective enough since it is only valid for homogeneous airflow (i.e without turbulence), and it depends on the proximity of the pointing device to the reference node; (2) the limited bandwidth of transducers restricts the number of users (tools) operating at the same time; (3) the system can only support 8 receivers (not scalable) and the location area is restricted to a square of 4×4 m (poor coverage); (4) the acoustic pattern of cylindrical transducer on the rod forces the receiving nodes to be on posts close to the excavation surface (intrusive system); additionally, (5) there is an excessive cabling among the PC and each node. These limitations encouraged us to design a new second LPS version for archaeology (3D-LOCUS), which is described in this paper.

The next section gives a thorough description of the new 3D-LOCUS LPS. Section 4 evaluates localization and sketching results in both laboratory and *Gran Dolina* site conditions. Section 5 discusses the main results found, and finally, the last section gives some conclusions.

3. 3D-LOCUS system description

3D-LOCUS is a new system for registering the three-dimensional location, shape and orientation of finds in archaeological digs. Its design took into account the performance and operativeness expected for most archaeological sites requiring a high level of recorded detail. Mainly those requirements are high accuracy, ease of use, and validity for different excavations. Our proposed solution inherits some of the features of the first LPS (Jiménez and Seco, 2005): long pointing devices and acoustic ranging. Additionally, 3D-LOCUS incorporates many new design improvements, e.g. transducers having a wide bandwidth, bidirectional signal propagation, wireless pointing devices, multiuser operation, and robustness to airflows. The next subsections give more details on these topics.

3.1. Design concept and functional description

A schematic representation of 3D-LOCUS system is depicted in Fig. 2. The key elements of the system are: (1) a network of nodes fixed over the excavation area having their transducers facing down, (2) an additional static reference node, facing up, for checking the integrity of measurements, (3) the pointing devices, with a node attached to them, which are the tools used by the archaeologists, (4) a central node for management of the network,

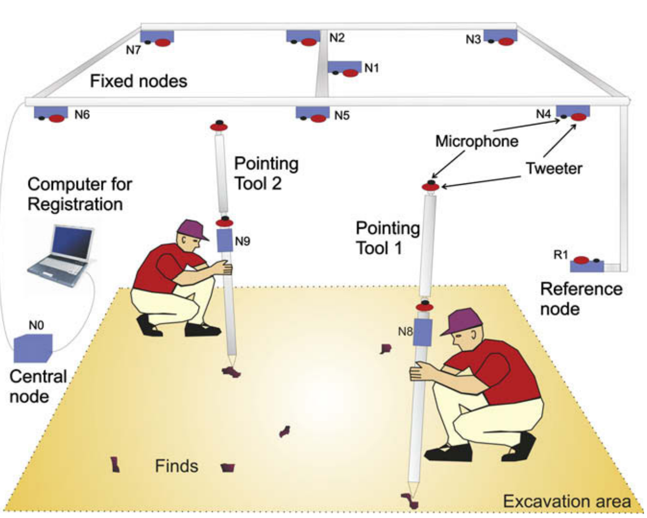

Fig. 2. 3D-LOCUS concept. Typical sensor network deployment and way of use.

and (5) a standard personal computer (PC) for registration and on-line visualization of data.

All nodes except the central node have at least two broadband omni-directional acoustic transducers for inter-node ranging: an audio tweeter and a microphone. The omni-directionality and wide bandwidth of selected transducers are required in order to achieve large coverage, multiuser operation, as well as accurate resistant-to-noise estimation.

The pointing devices manipulated by archaeologists are long light-weight rods. Each pointing device has two pairs of transducers: (1) one pair at the top of the rod, and (2) another pair about 70 cm below the first. Once the three-dimensional coordinates of both upper and lower transducers are estimated, the spatial location of the rod's lower tip is calculated by simple extrapolation. The use of a long rod as a pointing device permits a free-of-obstacles acoustic propagation among mobile and fixed nodes. Thanks to the elevated location of transducers, acoustic propagation occurs within the space over the bodies of diggers and any occluding material in the excavation. This mode of operation is essential to achieve a reliable localization even if provenance registration is done simultaneously to the digging labor.

The procedure to register the provenance of an object consists in: (1) placing the lower tip of the pointing device on its surface; (2) briefly pressing a button close to the handle of the device which triggers the emissions of several acoustic signals. Optionally, if the archaeologist needs to register the outline, shape and orientation of the object, the system can enter into a *continuous capture mode* by holding the button pressed while moving the lower tip along the silhouette of the object.

3.2. Network architecture

The 3D-LOCUS architecture (Fig. 3) consists of a network of nodes with advanced sensing, processing and communication capabilities. All nodes have the same hardware architecture based on a Digital Signal Processor (Texas F2812 DSP). This DSP allows the generation of arbitrary digital waveforms for acoustic transmission, and the implementation of advanced signal processing algorithms for accurate TOA estimation. Additional components are installed onto the DSP board to fit all the required functionalities (i.e. wireless or tethered communication, analog signal conditioning, synchronization, etc.).

The central node is tethered to the fixed nodes, to provide them with communication via a standard Controller Area Network (CAN) bus, and synchronization using a Low-Voltage Differential Signaling (LVDS) interface. On the other hand, the portable wireless nodes communicate with the central node via Bluetooth. These mobile nodes are powered with four rechargeable 1.2-V batteries (3700 mAh, NiMH). At least 12-h autonomy is achieved for a typical consumption of 300 mA per node. This guarantees that the pointing device can be used continuously during the typical working hours in the excavation.

The PC in 3D-LOCUS is used for storing the 3D spatial coordinates of finds (position and trace). It is connected to the central node through an RS-232C serial link. Additionally, the PC can be used to configure the behavior of the network. An extensive range of features can be set (Prieto et al., 2007; Prieto et al., 2009) to achieve an optimum performance (i.e. update rate, acoustic power, maximum range, signal coding, medium access, filtering, and others).

3.3. Rod designs

Two different pointing devices were designed and implemented: (1) a long pole with two pairs of transducers (a microphone/tweeter pair, one at the top and other at mid-height) (Fig. 4);

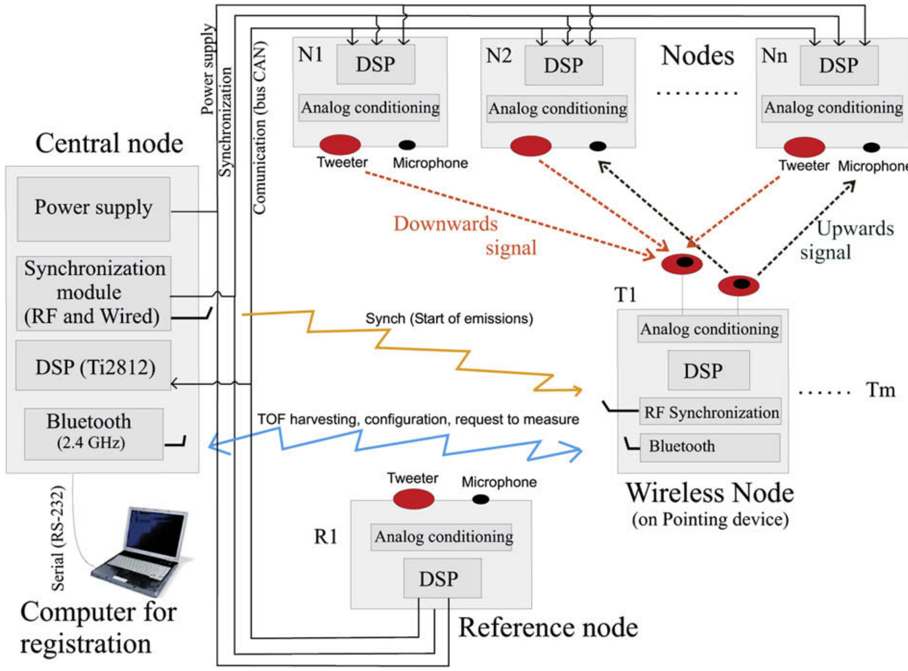

Fig. 3. 3D-LOCUS hardware architecture. A network of wired nodes are connected to a central node for power supply, synchronization and communication. Wireless nodes, which have to be installed on pointing devices, interchange acoustic signals (upward and downward) with fixed nodes. Wireless nodes are synchronized by an RF link and data communication is performed using Bluetooth. The central node is connected to a PC for final data registration.

and (2) a short pole with only one pair of transducers at the top and a self-levelling mechanism (Fig. 5).

In the long rod (Fig. 4), special housings were designed for each pair of adjacent transducers. The microphone is placed on top of the tweeter at a 60 mm distance along the rod's axis of symmetry. The tool is set up by connecting several segments of an aluminium pipe of 40 mm in diameter. The length of the device is almost 2 m. Two segments are slotted to let sound propagate with minimum interference. The lower tip can be tilted using a spherical joint to precisely align its end with the line passing through the center of both pair of transducers. This is required in order to obtain an accurate position extrapolation. A button is available to trigger measurements, but node's electronics (housed in a plastic box) and batteries (inside the hollowed lower segment) are protected.

The short rod design (Fig. 5) has a mechanism that automatically aligns the device vertically; consequently only one pair of transducers is needed. The lower segment is levelled with the insertion of a low-friction cardan joint inside the cylinder. An external handle is connected to one end of this joint (Fig. 5b). This handle has a button at an ergonomic position. Slight inclinations of the handle are compensated by the vertical alignment of the rod. With this new design we gain simplicity, a more compact tool with a total length of 1.1 meters, but at the cost of spending more time till the rod reaches equilibrium. As in the long tool design, the lower conic piece can be tilted so as to place its end perfectly below the center of transducers.

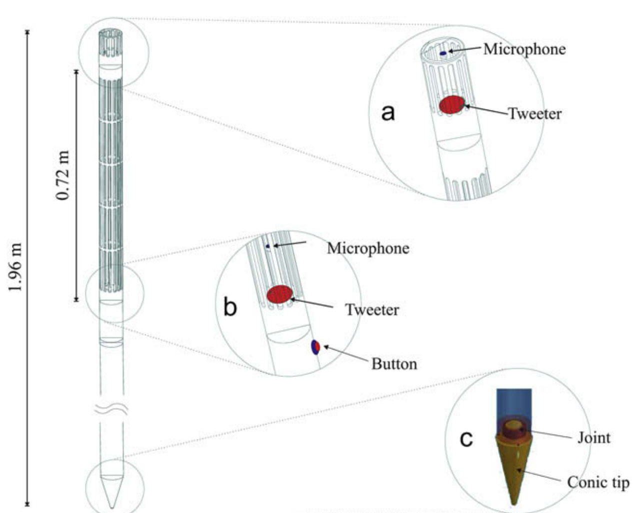

Fig. 4. Long dual-pair-of-transducers tool. (a) First pair of transducers at the top, (b) second pair at mid-height, and (c) the lower tip of the rod.

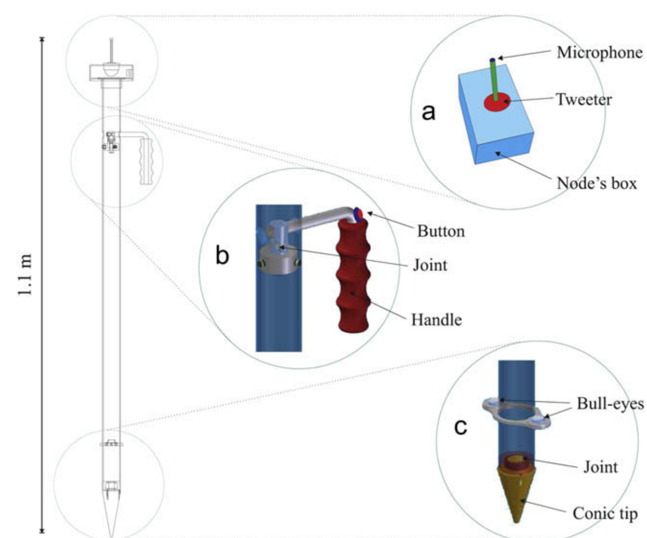

Fig. 5. Short self-levelled single-pair-of-transducers tool. (a) Vertical arrangement of both transducers on the node's box, (b) the handle with the rod's self-levelling joint, and (c) the lower tip with bull-eyes to check correct levelling.

For those experienced archaeologist who prefer to level the short rod manually, bull's eyes are installed at both sides of the cylinder (see Fig. 5c). This non-self-levelled mode of operation is valid for single measurements but we believe it is not very appropriate for continuous mode of operation since it requires a dynamic manual levelling.

3.4. Acoustic transducers and signal processing

In order to cope with 3D-LOCUS requirements we decided to use *broadband* and *omnidirectional* transducers, together with a spread-spectrum signal processing method that uses *pseudo-random noise* (PRN) digital codes. Since classical ultrasonic transducers do not cope with these features we decided to use acoustic transducers operating mainly in the audible region.

As the emitter, we use the CP13 tweeter from Visaton. It has a usable frequency band up to 25 kHz, and a wide emission pattern that is omnidirectional for audible frequencies. As the receiver, we use the WM61 microphone from Panasonic, which has a good sensitivity and an omnidirectional directivity at frequencies below 42 kHz (Prieto et al., 2007). The diameter of the tweeter and the microphone are 35 mm and 6 mm, respectively. Fig. 6 shows both transducers installed in one 3D-LOCUS node's box.

In order to avoid audible signals which can disturb archaeologists in the excavation area, emission frequencies were selected evading the frequency band were humans are most sensitive (2–5 kHz). Emitted signals use a bandwidth between 5 and 25 kHz, which is large enough to provide accurate ranging and good noise resistance. Signals are generated using a 15 kHz sinusoidal carrier modulated with PRN codes by Direct-Sequence Binary Phase Shift Keying (DS-BPSK) (Oppenheim et al., 1999).

To unambiguously identify each node and to allow multi-user operation, we use a unique Golay PRN codes in the signals generated by every node (Popovic, 1999). Long PRN codes provide accurate ranging but the detection capability can be degraded in turbulent airflow scenarios such as archaeological sites (Álvarez et al., 2006). A PRN code length of 32 chips was used as a compromise between *accurate ranging* and *detection capability*.

3.5. Node calibration for accurate ranging

If transducers are non-symmetric and the orientation between nodes varies, the accuracy of the measured ranges could be deteriorated. Reliable ranging with independence of node's orientation can be achieved if transducers are point-like or at least they behave as having a virtual center of emission or reception. In a previous work by the authors (Prieto et al., 2007), it was found that both tweeter and microphone behave as point-like transducers. A total ranging error of ±1.5 mm was found for an angular variation between transducers of ±90°. The virtual center of emission of CP13 tweeter was found to be 4.2 mm ahead from the surface of the box (Fig. 6) along tweeter's axis of revolution. The virtual center of reception of Panasonic's microphone is 0.4 mm ahead box's surface.

A second important issue for accurate ranging is the determination and compensation of any existing delay affecting TOF estimations. They can be caused by non-perfect RF synchronization, and also provoked by the joint transfer function of transducers and electronics. As presented in (Prieto et al., 2007), these delays were determined accurately for 3D-LOCUS nodes, being 82.8 μs for RF synchronization, and 128.6 μs for a joint transducer/electronics transfer function.

3.6. Bidirectional and redundant positioning

One of the major limitations of acoustic LPS, when used in outdoor sites, is the influence of wind on actual TOA. Wind from emitter to receiver, or downstream, increases propagation speed and therefore measured TOA are shorter than in calm air or upstream. Ideally, the effect of airflows on measured TOA depends on wind intensity along the propagation axis, V_{al}, and the actual range, r, between nodes; as given by the following equation $\Delta t = rV_{al}/V_s^2$, where V_s is the speed of sound in calm air and Δt is the final error in TOA.

A solution to this airflow problem was proposed in the first ultrasonic LPS for archaeology (Jiménez and Seco, 2005) that consisted in adding a reference node for estimating the three components of the speed of air. By including this anemometry information in the positioning algorithms, localization estimation was more reliable. However this procedure is only valid in the ideal case of uniform airflow. In a realistic terrain, like an archaeological site, airflows are not uniform but turbulent.

The approach in 3D-LOCUS consists in transmitting acoustic signals in both directions between every pair of nodes involved in the trilateration. In a first phase, nodes on the pointing device are

Fig. 6. Acoustic transducers (tweeter and microphone) installed in a 3D-LOCUS node.

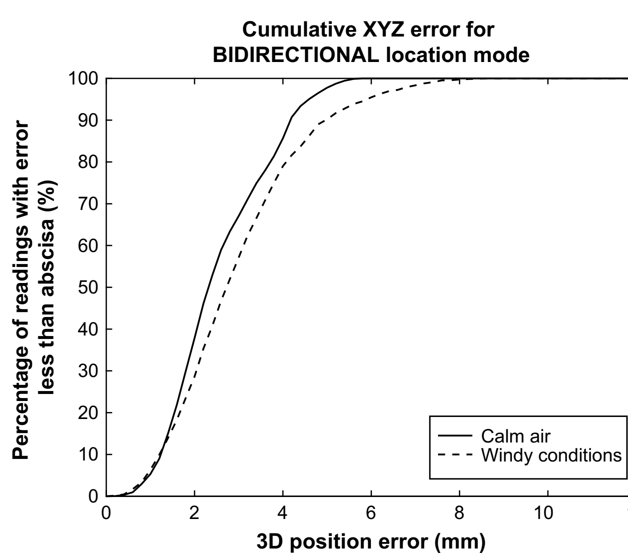

Fig. 7. Accuracy determination of 3D-LOCUS with a cumulative XYZ error representation.

initially configured to emit, and therefore, nodes fixed on the ceiling of the excavation are configured to receive (upward TOA estimation). In a second phase, nodes change their roles (downward TOA estimation). This bidirectional emission gives us enough information to estimate the wind magnitude and direction along the axis of propagation between nodes. The estimation of air influence is therefore local to that path, and consequently supports non-uniform and turbulent winds.

Initially, 3D-LOCUS estimates separately the position of the emitter and the microphone on the pointing device's node. After that, a weighted average of both emitter and receiver positions gives the airflow-compensated position estimation. Using the sequential bidirectional emission strategy, and assuming a maximum propagation distance of 8 meters between nodes and a typical propagation speed of sound in air (340 m/s), the maximum measurement update rate of 3D-LOCUS is about 10 Hz.

During on-site operation, the bodies of archaeologist can temporally occlude transducers or block acoustic propagation. This blockage could potentially affect the accuracy of estimations. To circumvent this problem, 3D-LOCUS operates with a redundant number of nodes. It means that we use more TOA than the minimum number strictly needed for trilateration. 3D-LOCUS includes an additional fixed node within the working volume (the reference node), to check the integrity and consistency of all estimations (Prieto et al., 2009).

4. Tests and performance evaluation

An assessment of the 3D-LOCUS performance is presented in the next sections. Among others, it considers location accuracy, resolution, capability to create meaningful sketches of finds, and robustness to attenuate the effects of airflows. The first batch of tests was conducted in laboratory conditions using a robotic manipulator for precise performance evaluation. The 3D-LOCUS system was additionally tested outdoors in the Gran Dolina

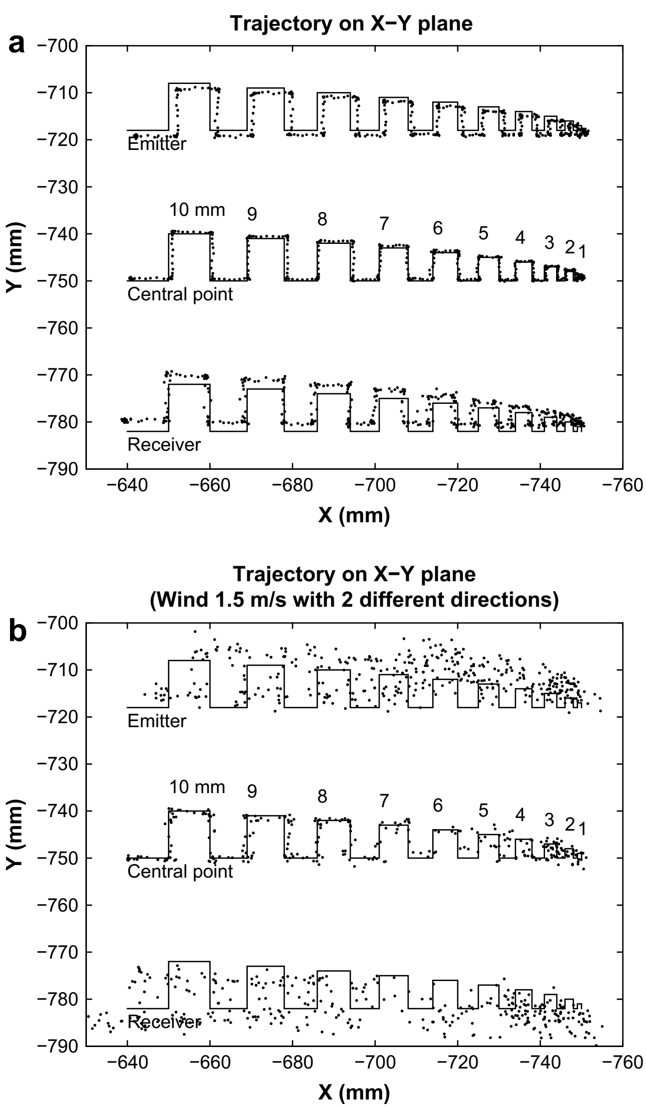

Fig. 8. Deducing 3D-LOCUS resolution with scale-decreasing square trajectory. (a) In calm air conditions. (b) In windy conditions. Real trajectories of emitter, receiver and central point in solid lines; estimated positions in dots. Note that 3D-LOCUS resolution can be deduced from dots close to real "central point" trajectory using the bidirectional information.

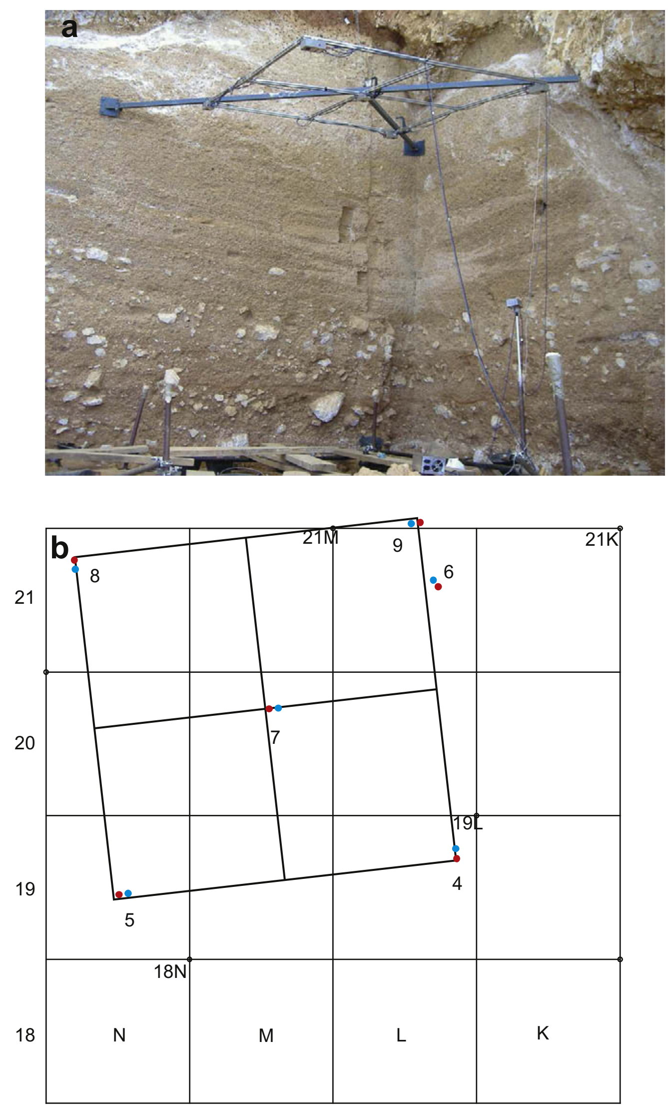

Fig. 9. Basic 3D-LOCUS infrastructure installed in Gran Dolina archaeological site. (a) Five fixed nodes are installed 4 meters above the excavation soil, and one reference node on a post at mid-height. (b) Position of the five fixed nodes (numbers: 4, 5, 7, 8 and 9) and the reference node (number 6) overlaid on a grid made of the cells covered by the system (cell identifiers made of numbers and letters are annotated). Dots close to node numbers represent the horizontal position of tweeters and microphones.

archaeological site, giving the excavators the opportunity to use the two types of tools (Section 3.3) for provenance registration.

4.1. Location accuracy and wind influence

Before the installation of the system in Gran Dolina, we evaluated the 3D-LOCUS positioning accuracy in laboratory conditions. This tests were performed using a network of seven fixed nodes placed on a frame at a height of 3 m above the floor. In order to evaluate the system accuracy with enough exactitude, we employed a Staübli RX90 robotic manipulator as a ground truth. The mobile node was affixed to the wrist of the manipulator and then moved at 22 different positions within the available working volume of the robot. At each position we captured sequences of more than 200 measurements in windy and calm air conditions.

The wind was created using an industrial fan able to generate airflows up to 5 m per second. The cumulative errors in localization using the bidirectional compensation method are presented in Fig. 7. In ideal conditions the positioning error is below 5 mm in 98% of the occurrences; a slight deterioration is perceived in windy conditions but is below 7 mm at the same confidence level. Errors are no larger than 8 mm, which is an important fact demonstrating the robustness of the estimation process.

4.2. Trace resolution

In order to evaluate the real capability of the system to sketch an object, we firstly studied its resolution, i.e. the minimum tool displacement that causes a significative change in the position estimation. For resolution estimation we moved the Stäubli robot along a trajectory that reproduces a sequence of decreasing-size squares (10 consecutive steps, with a 1 mm decrease per step, starting at 10 mm). Fig. 8 shows with solid lines the real trajectories described by the tweeter, the microphone and the mid-point between both transducers that form part of the mobile node.

The estimated tweeter's positions, using only upward emissions in calm air conditions, are represented with a trail of dots close to the real emitter trajectory in Fig. 8a. Under the same conditions, the estimated microphone's position is shown with dots in this figure. Some bias is detected on microphone and tweeter trajectories with respect to the actual path, probably due to errors while positioning the mobile node on manipulator's wrist or other calibration errors. The average of both independent position estimations, represented by the intermediate trail of dots in Fig. 8a, is found to perfectly fit the mid-point real trajectory. From these results it can be deduced a discernible resolution of about 2 mm.

The resolution was also evaluated in variant windy conditions. The individual estimations of tweeter and microphone are significantly affected in accuracy and resolution, as can be seen in Fig. 8b (upper and lower cloud of dots). However using the bidirectional compensation method proposed in 3D-LOCUS, not only accuracy is improved (as shown in last section) but the resolution is kept without too much degradation. The discernible resolution is approximately 5 mm.

4.3. Deployment in Gran Dolina

The purpose of the 3D-LOCUS tests in Gran Dolina was to validate its functionality and to get feedback from excavators for further refinements. Since the goal was not yet to substitute the current method of registration, we only covered a fraction of the whole excavation site using a minimal sensor network infrastructure.

The 3D-LOCUS installation in Gran Dolina, apart from a PC and a central node, comprised a network of five fixed nodes, a reference node and two pointing devices (the long and short rods). A square structure of 2.4 m side was installed 4 m above the site's terrain (Fig. 9a). Affixed to this structure, five nodes (numbered 4, 5, 7, 8 and 9) are attached in locations shown in Fig. 9b. This 3D-LOCUS deployment covers an area of 16 m^2. The wired reference node, for integrity monitoring (numbered 6), is placed at a fixed position over the excavation soil.

The exact 3D position of sensing nodes (microphone and tweeter) was calibrated using a Trimble 3605 total station. Since the total station was referenced to the excavation coordinate frame, the 3D-LOCUS nodes are also referred to the same frame as well as all position estimations.

The excavators used the pointing devices, as shown in Fig. 10. The estimated 3D location of the lower tip of the rod was displayed on the PC's screen for immediate feedback (Fig. 10c). This information can include the absolute coordinates, or alternatively the more usual representation relative to a unit cell (cell identity plus relative coordinates).

4.4. Robustness to turbulent airflows

The bidirectional compensation method to robustly estimate location has been experimentally tested in Gran Dolina. Some of the tests in Gran Dolina under windy conditions are shown in Fig. 11a. The measured upward and downward TOA are shown in dashed and dotted lines, respectively. In this case the propagation is between reference node 6 and some fixed nodes above the

Fig. 10. Using the 3D-LOCUS system in Gran Dolina dig. (a) The short self-levelled rod. (b) The long dual-sensor rod that does not require prior levelling before measuring. (c) Display of position estimation relative, in this case, to cell 19L.

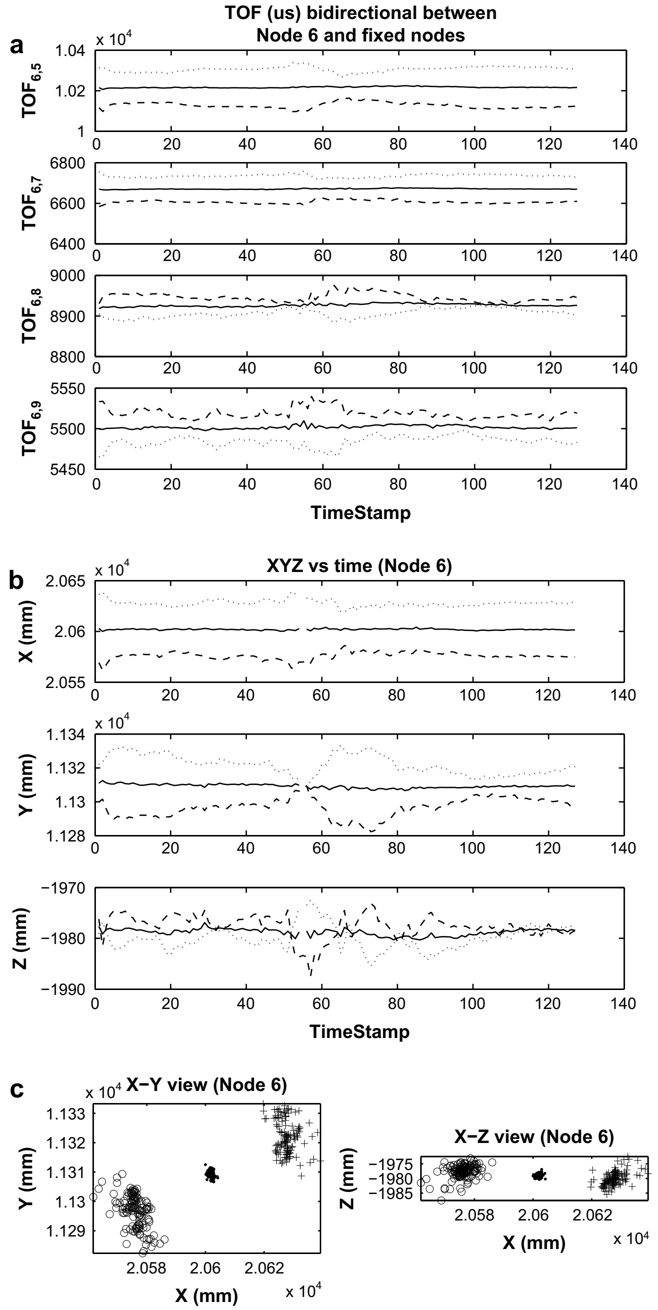

Fig. 11. Wind effects on TOA and XYZ estimations, and results of the bidirectional compensation method. (a) Airflow influence on individual TOA (dashed and dotted lines) and bidirectional compensation by TOA averaging (solid line). (b) Airflow influence on individual XYZ estimations (dashed and dotted) and bidirectional compensation by XYZ averaging (solid). (c) Same case that in (b) but spatially plotted on to XY and XZ planes. Note that bidirectional estimations (dots) have a much lower dispersion than individual estimations (circles and pluses).

excavation (nodes 5, 7, 8 and 9). Note how the effect of wind on TOA is opposite, and greatly compensated by taking the average.

Airflow causes errors in the estimated position of transducers. These errors are a function of wind velocity but we found that they approximately have opposite directions for tweeter and microphone estimations. Fig. 11b shows the estimated position of tweeter (dashed line plot) and microphone (dotted line). Note how wind causes approximately 2 cm error in transducer positions, but the direct average of tweeter and microphone coordinates (solid line plot) gives a much more stable estimate. The same data projected on the XY and XZ planes are displayed in Fig. 11c. The averaged cluster (dotted cloud) has a much lower dispersion as compared to transducer's position estimations (circle and plus clouds). These results satisfy accuracy requirements demanded in outdoor archaeological excavations for detailed provenance registration.

4.5. *Object's volumetric registration*

The capability of 3D-LOCUS to obtain reliable volumetric information from objects was evaluated. The first test consisted in sketching an artificial pyramid-like object (Fig. 12a) which includes large edges (up to 8 cm long in its base) and small spatial details, i.e, a sloped tail of about 1-cm-side at one of the pyramid facets. A sequence of spatial coordinates is captured while the tip of the pointing device is moved along the edges of the object. The system automatically low-pass filters the data, eliminating manual tremors during registration. This filtered trace is presented in Fig. 12b and c. We see that the size and shape of the object are correctly captured, as well as the small details in one of its facets.

Other more realistic tests were performed with groups of natural and artificial objects. The objective was to verify that the system captures the volumetric shape of every object, as well as their relative inter-object distance and orientation. A replica 1-m^2 unit cell with 21 objects of different sizes and shapes (see top of Fig. 13) was employed. Because of the 5-mm resolution of the system in outdoor or windy environments, only objects with a volume larger than 1 cm^3 were digitalized. The measurement was made with the short pole. We captured the contour of the object as well as some significant edges getting volumetric information. The profile obtained for each object is shown in Fig. 13 in 2D and 3D. Note that the inter-object distance and orientation is perfectly captured; the sketches of every object on the XY plane are of slightly bigger size than in reality, since the lower tip of the pointing device is not sharp (spherical end with 5 mm of diameter).

5. Discussion

The ultimate goal of 3D-LOCUS research is the substitution of the traditional way of provenance registration by a more reliable and efficient methodology. In order to achieve this final goal, important additional topics will be discussed before defining new actions towards improving current 3D-LOCUS functionalities. These include: reliability of tool designs, manipulation by the archaeologist, difficulties to setup the system in the excavation, capability of the system to operate in different excavations, filtering and integrity monitoring of estimations, new technologies for improving the hardware design, or expected cost of equipment for full deployment.

Two different tool designs (Section 3.3) were tried in order to check which one is more reliable and better accepted by the archaeologist. The short self-levelled single-pair-of-transducers tool is more compact, uses less electronics, and it is very accurate in determining the position of static points. However, the reliability of sketches could be deteriorated if the tool's tip tended to oscillate like a pendulum. The longer tool design has the main benefit that the position and inclination of the rod is accurately estimated, so the tool can be used unlevelled. However the position estimation has a dispersion (standard deviation) that is approximately twice the obtained with the short tool under static measurements. This increase in dispersion is caused by the amplification of errors when extrapolating coordinates from the two pairs of transducers to obtain the lower tip's position. Nevertheless, a higher dispersion does not mean a poorer trueness, which is similar in both tool designs under static measurement. These reasons justify the

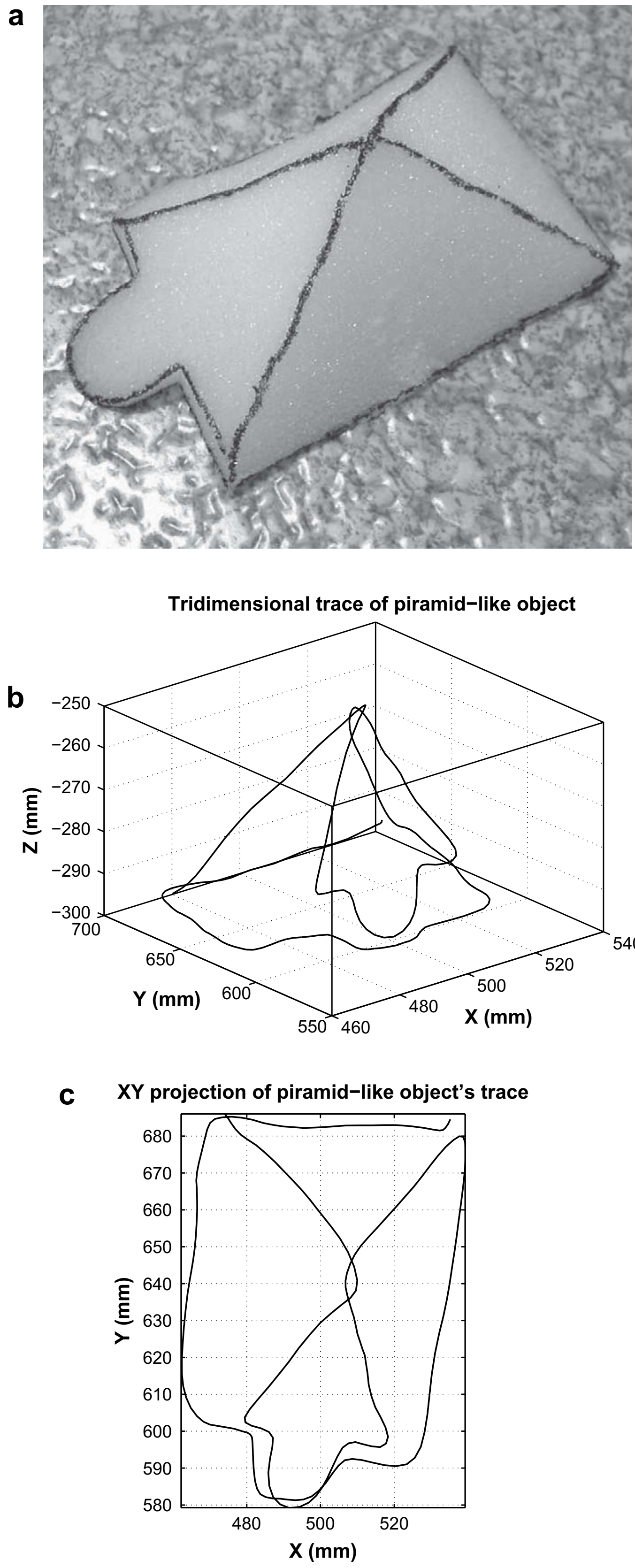

Fig. 12. Sketching a regular object using 3D-LOCUS. (a) A pyramid-like object with some low profile details and straight and curved edges (size: L 80 mm × W 60 mm × H 45 mm). (b) Resulting estimated 3D trace of this object. (c) Projection of 3D trace on XY plane (traditional representation of find's shape).

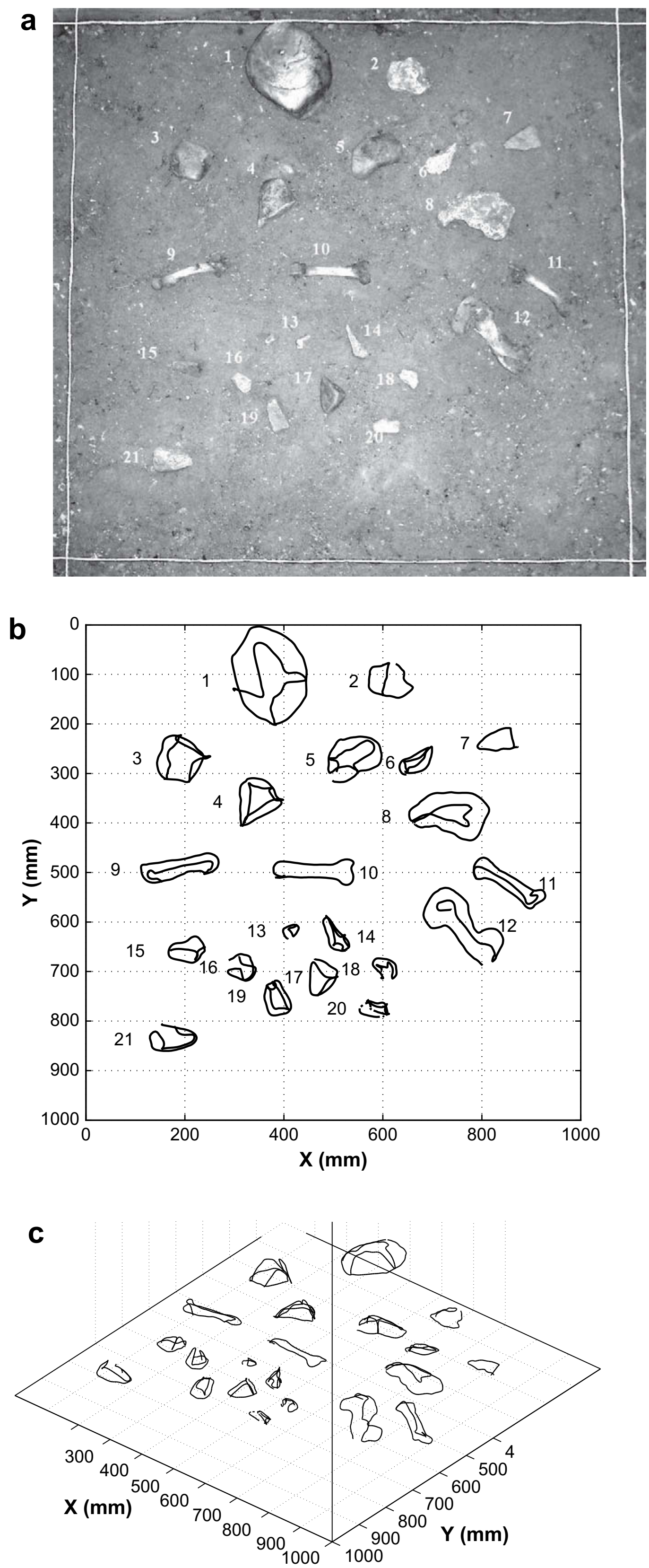

Fig. 13. Sketching, with 3D-LOCUS, several objects within a square cell of 1 m side. At the top, a photograph of the cell containing 21 objects. In the middle, an XY projection of the traces captured with 3D-LOCUS. At the bottom, a 3D representation of captured traces.

filtering of position estimations from both tool designs to alleviate the oscillation impact and the extrapolation effects.

From the archaeologists' point of view, the short self-levelled tool it is not ideal for tracing object's contours, since the pointing device has to be moved with one hand very slowly to avoid pendular oscillations. If they occur, the other hand has to be used to attenuate them (see Fig. 10a). Since the short tool is prepared to be vertically aligned, it is not valid for registering objects in places where the tool cannot be kept upright (e.g. object close to a wall that is inclined over the excavation area). On the other hand, the long tool design, is heavier and bulkier. It has to be manipulated with both hands, one positioned at the tool's center of mass to hold its weight, and the other one close to the lower tip, pointing to the location of interest. The main advantage is that the long tool can be manipulated in a more agile and quick manner. Besides, the tool can be inclined to locate objects in areas of difficult access. For these reasons, most of the archaeologists believe that the long rod design is more versatile and easy to use.

During measurement it is recommended not to contact the lower tip of the pointing device with the object to avoid any damage or displacement of the find. For that reason, when the user presses the button to start a measurement, the tool tip should be a few millimeters away from the object's surface, until the measurement ends. The archaeologist knows when measurements are being taken place because he/she receives an acoustic feedback. This sound beep is created by the acoustic emissions for inter-node ranging, which have part of their transmitted energy band (5–25 kHz) in the audible region. This way of operation has resulted positive from the point of view of archaeologists to let them know when measurements actually take place.

The current 3D-LOCUS prototype has been tested with two pointing devices operating in parallel. These tests were restricted by the number of tools available, but the design is prepared to admit more tools in parallel. The requests prompted by each tool to start a measurement are attended by time-multiplexing by the central node. Since the update rate for a single tool is about 10 Hz, the response time after a button is pressed in a tool depends on the number of simultaneous requests. It is expected a maximum delay of 1 s, between the action of pressing a button and the actual beginning of the measurement, if 10 tools are requesting a single point measurement at the same time. For continuous measurements (sketching objects) the number of parallel sketches is more limited. A maximum of two sketches at a time is recommended in order to avoid the acquisition of too few points per trace.

Each tool has its own identification code, so parallel measurements are not confused, and the central node knows which position estimation corresponds to what tool. Additionally, although not implemented yet in the current prototype, 3D-LOCUS tools could use their Bluetooth channels to receive a unique identification label for the particular find under provenance. This is possible since archaeologists in Gran Dolina already obtain a unique identification label per find while they use a PDA (Personal Digital Assistant) for annotating other descriptive features such as the find's taxonomy. A server computer is in charge of generating new identification labels whenever a PDA requests the storage of data in the server database. This is a very interesting feature that could guarantee the integrity of data (object ID, position, taxonomy, etc.) in a unique record in the excavation database.

The 3D-LOCUS system can be adapted to the shape and size of a particular dig, by adequately distributing the necessary number of nodes over the excavation. For this purpose, the authors have developed a software tool (Laguna et al., 2009) that, given a desired area for localization and the type of transducers used, generates an optimal layout of nodes that minimizes cost (number of nodes) while giving maximum accuracy and coverage.

In order to install the network of sensor nodes over the excavation, a specially designed frame or ceiling is needed to secure the nodes at fixed positions. To avoid the re-calibration of all nodes frequently, which could take a couple of hours, it is recommended to do the installation once at the beginning of the excavation campaign, and keep it until the end of the season. This procedure means to leave the sensors overnight, which is problematic if the site is not watched out because vandals could damage the equipment. Nevertheless, as sensors are placed at a significant height above the terrain (4 m), damage is not too likely. The maintenance of the equipment during the excavation campaign only consists in charging the batteries of each tool during the night.

3D-LOCUS was tested in open-spaces and in trenches, however the installation of 3D-LOCUS in caves could also be possible. Reverberation in a cave could affect 3D-LOCUS performance due to multipath propagation. A further study should be done to check its operation in caves and to determine if it is necessary to include advanced multipath-cancellation techniques.

Noise reduction techniques such as Kalman filters are a common practice to reduce the variance of noise-corrupted estimations. The positioning results presented along this paper for accuracy and resolution determination are obtained without the help of any Kalman-like filter. The only results that are automatically smoothed (for tremor suppression) are those presented in Figs. 12 and 13 corresponding to the profiling of objects. The implementation of Kalman filters, robust estimators and auto-calibration methods will further improve the results already presented, making possible very repetitive estimations and probably errors below 5 mm in almost all conditions.

Some new technologies could be used to improve the hardware design of 3D-LOCUS. One possibility could be to convert all sensing nodes to wireless using mesh-like or ad-hoc communications protocols (e.g. Zigbee). If so, cabling among nodes would be eliminated and a more flexible non-centralized inter-node communication could be implemented. The energy for powering nodes could be obtained from batteries connected to local solar panels. Additionally, other types of omnidirectional broadband transducers could be used in order to increase the number of simultaneous pointing devices in a dig, and to minimize the number of nodes for a complete installation (*Gran Dolina* could need about 20 nodes). Some new transducer designs based on ferroelectrectric films are being studied by our group to achieve this goal (Ealo et al., 2006, 2008).

The cost of the equipment required to achieve a full 3D-LOCUS deployment on a excavation is very important. The most expensive components within a node are the Texas Instruments 2812 DSP chip (25 $), the Visaton CP13 tweeter (40 $) and the Bluetooth communication module (50 $). At this stage we cannot assume wholesale prices, therefore retail costs imply a minimum of 250 $ per node. This means that a 100 m^2 excavation needing a total of 20 fixed nodes, a pair of reference nodes, two rod tools, a central node and a laptop computer, can cost about 8000 $ (no engineering and fabrication costs included). Consequently, the price for a 3D-LOCUS-like provenance registration equipment is expected to be similar to a common mid-performance total station (about 15,000 $). After a hypothetical commercial exploitation of 3D-LOCUS prototype, a decrease in equipment costs is expected, but this effect would be dictated by the volume market of archaeological sites around the world.

6. Conclusions

This paper has presented a new sensor equipment (3D-LOCUS) based on the bidirectional acoustic propagation of signals in air to measure the three-dimensional position of finds in archaeological excavations. This system can also be used to trace the outline of natural objects and artifacts, and therefore to accurately register their size, shape and orientation. In the paper, we described the 3D-LOCUS architecture, which consists of a network of distributed intelligent nodes installed above the excavation site, a central node for centralized synchronization and communication, a personal computer, and some portable wireless tools. Advanced processing DSP-based platforms and broadband transducers in each node allow the use of spread spectrum signal coding in order to achieve multiple access and good ranging accuracy. A bidirectional trilateration scheme is used to minimize errors provoked by turbulent airflows. Tests in laboratory conditions and in a real excavation site were performed.

The typical location accuracies obtained without filtering are below 10 mm in natural conditions, and the achieved resolution is about 5 mm. Results are good at obtaining the find's profile on the horizontal plane, and also capturing significative edges on its surface. The long rod resulted easier to manipulate and more versatile. The time required to capture objects, after some initial training, is faster than manual drawing, and is more accurate, since it places objects correctly in space capturing simultaneously location, shape and orientation.

The next actions to improve 3D-LOCUS prototype, probably will be focused towards improving the ergonomy and ease of use of tools; applying robust techniques to filter out Gaussian and non-Gaussian noise; employing communication protocols like Zigbee to create a total mesh-like wireless node network; and studying new transducing methods to further reduce the node density to cover an excavation area. The study of the applicability of the system in caves can also be investigated by implementing multipath cancellation techniques. It also would be desirable to have a faster installation and calibration of the system.

We believe that the 3D-LOCUS concept and realization represents a significant contribution in the computerization of archaeological sites. It has the ultimate goal of replacing the traditional way of provenance registration by a more reliable and efficient methodology. A practical consequence of this new methodology is a significant reduction of the time needed by an archeologist to capture and verify that their spatial annotations and drawings are correct. This data could be automatically transferred to a database in conjunction with other find's features. These facts finally imply a more productive and efficient excavation. Consequently more time will be available for the analysis and interpretation of results, and less for non-scientific systematic tasks.

Acknowledgements

This work has been supported by the Spanish *Atapuerca Foundation* who also helped in the evaluation of the system in the *Gran Dolina* archaeological site. The fundamental acoustic positioning research was funded by the Spanish Ministry of Science and Technology under PARMEI research (Ref. DIP2003-08715-C02-02) and some other previous projects.

References

Álvarez, F.J., Ureña, J., Mazo, M., Hernández, A., García, J.J., Marziani, C., 2006. High reliability outdoor sonar prototype based on efficient signal coding. IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control 53 (10), 1862–1871.
Bahl, P., Padmanabhan, V.N., 2000. Radar: an in-building user location and tracking system. In: Proceedings of the IEEE Infocom, Tel Aviv. pp. 775–784.
Balakrishnan, H., Priyantha, N., 2003. The cricket indoor location system: experience and status. WorkShop on location-aware computing, Ubicomp, p. 7–9.
Colosi, F., Gabrielli, R., Rose, D., 2001. Integrated use of DGPS and the total station for the survey of archaeological sites: the case of Colle Breccioso. Computing Archaeology for Understanding the Past. Computer Applications and Quantitative Methods in Archaeology. Archaeopress, Oxford, pp. 9–12.
Dibble, H.L., 1987. Measurement of artifact provenience with an electronic theodolite. Journal of Field Archaeology 14, 249–254.
Dibble, H.L., McPherron, S.P., 1988. On the computarization of archaeological projects. Journal of Field Archaeology 15 (4), 431–440.
Doran, J.E., Hodson, F.R., 1975. Mathematics and Computers in Archaeology. Edinburgh University Press.
Ealo, J.L., Jiménez, A.R., Seco, F., Prieto, C., Roa, J., Ramos, F., Guevara, J., 3–6 October 2006. Broadband omnidirectional ultrasonic transducer for airborne ultrasound based on EMFi. IEEE International Ultrasonics Symposium, Vancouver-CA, pp. 544–545.
Ealo, J.L., Seco, F., Jiménez, A.R., 2008. Broadband EMFi-based airbone ultrasonic transducers for robotic applications. IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control 55 (4), 919–928.
Fernández-Jalvo, Y., Andrews, P., 1992. Small mammal taphonomy of Gran Dolina, Atapuerca (Burgos), Spain. Journal of Archaeological Science 19, 407–428.
Fontana, R.J., Gunderson, S.J., 2002. Ultra-wideband precision asset location system. In: Proceedings of IEEE Conference on Ultra Wideband Systems and Technologies, Baltimore, pp. 147–150.
Hazas, M., Hopper, A., 2006. Broadband ultrasonic location systems for improved indoor positioning. IEEE Transactions on Mobile Computing 5 (5), 536–547.
Hightower, J., Borriello, G., 2001. Location systems for ubiquitous computing. IEEE Computer 34 (8), 57–66.
Jiménez, A.R., Seco, F., 2005. Precise localisation of archaeological findings with a new ultrasonic 3D positioning sensor. Sensors and Actuators A 123–124, 224–233.
Koutsou, A.D., Seco, F., Jiménez, A.R., Roa, J., Ealo, J., Prieto, C., Guevara, J., 3–5 October 2007. Preliminary localization results with an RFID based indoor guiding system. IEEE International Symposium on Intelligent Signal Processing, Alcalá de Henares, Spain, pp. 1–6.
Krumm, J., Harris, S., Meyers, B., Brumitt, B., Hale, M., Shafer, S., 2000. Multi-camera multiperson tracking for easyliving. Third IEEE International Workshop on Visual Surveillance (VS2000), pp. 3–10.
Laguna, M., Roa, J.O., Jiménez, A.R., Seco, F., 2009. Diversified local search for optimal layout of beacons in an indoor positioning system. IIE Transactions Desing and Manufacturing 41 (3), 247–259.
Martín-Abreu, J.M., Jiménez, A.R., Seco, F., Calderón, L., Pons, J.L., Ceres, R., 2002. Estimating the 3D-position from time delay data of us-waves: experimental analysis and new processing algorithm. Sensors and Actuators A 101, 311–321.
McPherron, S.J.P., 2005. Artifact orientations and site formation processes from total station proveniences. Journal of Archaeological Science 32, 1003–1014.
Misra, P., Enge, P., 2006. Global Positioning System: Signals, Measurements, and Performance. Ganga-Jamuna Press, MA, ISBN 0-9709544-1-7.
Ni, L.M., Liu, Y., Lau, Y.C., Patil, A.P., 2004. Landmarc: indoor location sensing using active RFID. Wireless networks. Special Issue on Pervasive Computing and Communications 10 (6), 701–710.
Oppenheim, V., Schafer, R.W., Buck, J.R., 1999. Discrete-Time Signal Processing. Pretince Hall.
Popovic, B.M., 1999. Efficient Golay correlator. Electronics Letters 35, 1427–1428.
Prieto, J.C., Jiménez, A.R., Guevara, J., Ealo, J., Seco, F., Roa, J., Ramos, F., 3–5 October 2007. Subcentimeter-accuracy localization through broadband acoustic transducers. IEEE International Symposium on Intelligent Signal Processing, Alcalá de Henares, Spain, pp. 1–6.
Prieto, J.C., Jiménez, A.R., Guevara, J., Ealo, J., Seco, F., Roa, J., Koutsou, A., 6–8 May 2008. Robust regression applied to ultrasound location systems. In: Proceedings of IEEE/ION PLANS, Monterey, California, USA, pp. 181–186.
Prieto, J.C., Jiménez, A.R., Guevara, J., Ealo, J., Seco, F., Roa, J., Ramos, F., 2009. Performance evaluation of 3D-LOCUS advanced acoustic LPS. IEEE Transactions on Intrumentation and Measurement 58 (8), 2385–2395.
Schindler, K., Grabner, M., Leberl, F., 2003. Fast on-site reconstruction and visualization of archaeological finds. In: Proceedings of CIPA Symposium, Antalya, Turkey.
Tack, F., Debie, J., Goossens, R., De Meulemeester, J., Devriendt, D., 2005. A feasible methodology for the use of close range photogrammetry for the recording of archaeological excavations. In: XX CIPA International Symposium, Torino, Italy.
Want, R., Hopper, A., Falcao, V., Gibbons, J., 1992. The active badge location system. ACM Transations Information Systems 10, 91–102.
Wheatley, D., Gillings, M., 2002. Spatial technology and archaeology. The Archaeological Application of GIS. Taylor & Francis, London.
Werb, J., Lanzl, C., 1998. Designing a positioning system for finding things and people indoors. IEEE Spectrum, 71–78.