This article has been accepted for publication and undergone full peer review. Please cite this article as:

Costa C., Figorilli S., **Proto A.R.**, Colle G., Sperandio G., Gallo P., Antonucci F., Pallottino F., Menesatti P., 2018. DIGITAL STEREOVISION SYSTEM FOR DENDROMETRY, GEOREFERENCING AND DATA MANAGEMENT.

**Biosystems Engineering** 174: 126-133.
https://doi.org/10.1016/j.biosystemseng.2018.07.003

# Digital stereovision system for dendrometry, georeferencing and data management

Corrado Costa [1]*, Simone Figorilli [1], Andrea Rosario Proto [2], Giacomo Colle [3], Giulio Sperandio [1], Pietro Gallo [1], Francesca Antonucci [1], Federico Pallottino [1], Paolo Menesatti [1]

[1] Consiglio per la ricerca in agricoltura e l'analisi dell'economia agraria (CREA) - Centro di ricerca Ingegneria e Trasformazioni agroalimentari, Via della Pascolare 16, 00015 Monterotondo (Rome), Italy.

[2] Department of AGRARIA, Mediterranean University of Reggio Calabria, Feo di Vito, 89122 Reggio Calabria, Italy.

[3] Effetreseizero Srl, Spinoff CREA, Via dei Solteri 37/1, 38121 Trento, Italy.

* Corresponding author. Phone.: +39 06 906 75 214; fax: +39 06 906 25591. E-mail address: corrado.costa@crea.gov.it

**Research Highlights**

- Stereovision for in-field estimation of tree height and diameter
- Mobile Android app for the management and georeferencing of stereo images
- Comparison of measurements - reference (felled trees) and stereovision
- No significant differences between stereovision and traditional methods

**Abstract**

A stereovision system for the in-field estimation of trees parameters such as height and diameter is proposed. The system includes a specifically developed mobile application for the management and georeferencing of stereo images. Stereo imaging allows the measurement of the distance between two points using triangulation formulas for the extraction of three-dimensional coordinates. The methodology is structured following three phases: training  using system calibration through stereovision analysis of known artificial known objects; testing using measurements of standing tree diameters and heights acquired through stereovision system, laser rangefinder (height) and tree calliper (diameter); field application testing using direct height and diameter measurements in natural and urban woods. For this last phase an Android application was developed. The results show that the error between direct measurements and those measured with both stereovision and traditional reference methods (laser rangefinder and tree calliper) were quite low: 6.8±6.6% between direct and laser rangefinder height measurements; 5.8±5.5% between direct and stereovision height measurements; 4.2±3.0% between direct and stereovision diameter measurements. No significant difference was found between the different methods for estimating height and diameter. Around 200 images matched to stereovision acquisitions were acquired and georeferenced using the application.

**Keywords**

Stereo images; image analysis; tree diameters; tree heights; Android application.

## Nomenclature table

| | |
|---|---|
| ALS | Airborne Laser Scanning |
| CSV | Comma-Separated Values |
| DGNSS | Differential Global Navigation Satellite Systems |
| GNSS | Global Navigation Satellite Systems |
| GPS | Global Positioning System |
| JPG | Joint Photographic Group |
| JSON | JavaScript Object Notation |
| KML | Keyhole Mark-up Language |
| LAI | Leaf Area Index |
| LIDAR | Light Detection And Ranging |
| PHP | Hypertext Pre-processor |
| RGB | Red Green Blue |
| SD | Standard Deviation |
| SLR | Single-Lens Reflex |
| TLS | Terrestrial Laser Scanner |
| VTA | Visual Tree Assessment |

## 1. Introduction

Wood volume is one of the most important parameters required for the evaluation of forests. It is used to assess tree growth and to monitor natural resources in order to apply proper maintenance (Herrera et al., 2011). To calculate wood volume accurately is necessary to precisely acquire dendrometry parameters such as height and diameter. These parameters are also used to indicate the status of tree health, when referred to a population, or to classify the mechanical danger in relation to the probability of tree toppling (Smiley et al., 2007). Also, identification of timber species and estimation of the quantity and quality are of timber are critical for quantifying the productive value of a forest (Proto et al., 2017). Furthermore, the same parameters are crucial in timber industry for various commercial and logistic purposes (Gutzeit & Voskamp, 2012).

Computer vision applications are rapidly increasing in their scope and performance and have become important ready-to use tools in the forestry sector. Some applications are available to calculate leaf area index (LAI; Chianucci & Cutini, 2013), texture (Bai et al., 2005), basal area and diameter distribution (Gobakken & Næsset, 2004. These techniques, also provide solutions for automatically determining log quality and grade, without the necessity to climb tree, thereby improving the accuracy and precision of upper diameters when estimating standing trees (Herrera et al., 2011). For example, in the study by Brownlie et al. (2007), a digital image-based dendrometry system was developed to provide accurate dimensional and positional measurements of the branches, whorls and stems of standing trees. This included sweep and three-dimensional (3D) position. Tree stereo digital images are acquired and some field parameters are measured for their association with a particular image/object environment. Firth et al. (2000) acquired high resolution RGB pictures of tree stems to describe the camera-to-object (*i.e.*, tree) geometry.

Although computer vision techniques are widely available and applied for the volume calculation of the wood log piles, only a few studies report the use of these technologies to calculate dendrometry parameters for single standing trees (Firth et al., 2000; Brownlie et al., 2007). Fink (2004) applied classical vision algorithms and active contours to identify log cut surfaces. The procedure they proposed worked semi-automatically making assumptions on wood type, lighting conditions and image quality. The method proposed by Dahl et al. (2006), consisted of a measuring system based on stereovision with a structure relying on two cameras. The area of wood section was calculated beforehand by using stereovision algorithms. This method estimated the percentage of wood in the measurement of wood log piles and worked only with clear images without disturbing factors. Herrera et al. (2011) present a strategy for computing disparity maps from hemispherical stereo images obtained with dedicated fish-eye lenses. To obtain appropriate measures of vegetation structure at multiple spatial scales in forest and in urban environments is normally challenging. Remote sensing provides tools can measure vegetation structure working across large areas (Kerr & Ostrovsky, 2003) and it plays an important role within the field of forest inventory. Airborne laser scanning (ALS) has also become an effective tool for acquiring forest inventory data. The georeferencing of these field plots is typically carried out by means of differential global navigation satellite systems (DGNSS) and normally relies on logging times of 15-20 min ensuring adequate accuracy under different forest conditions (Hauglin et al., 2014). Until recently, most remotely sensed data only provide only two-dimensional (2D) information (Seavy et al., 2009) and information regarding the structure of vegetation, which requires 3D to obtain for example tree heights, was has not been available. Light detection and ranging (LIDAR) is a remote-sensing technique that can provide detailed information on vegetation structure. LIDAR imagery can be generated using low-flying aircraft to record the reflection data and measure the height of objects beneath the aircraft (Lefsky et al. 2002). LIDAR imagery has been used to estimate the canopy height, stem diameter, canopy cover, biomass and other components of vegetation structure (Chasmer et al. 2006, Clawges et al. 2007). However, since the spatial extent and spatial resolution of a given sensor are inversely related (Franklin et al., 2002) the vegetation structure characterisation of large areas, based on remotely sensed data, often have sub-optimal precision for several applications (Xie et al., 2008).

Simonse et al. (2003) used a terrestrial laser scanner (TLS) for tree identification and to assess tree characteristics such as their positions and the diameters at breast height. This instrumentation presents a great accuracy of the data and the advantage of this technique is to obtain repeatable results of measurements because of the high level of automatism. However, the system was very expensive.

This study proposes a smart, cost-effective, mobile stereovision system for in-field estimation of dendrometry parameters (*i.e.*, heights and diameters). The system includes a specifically developed mobile application for the management and georeferencing of the stereo images. The use of stereo images allows the measurement of the distance between two points using formulas for triangulation of the 3D coordinates and angles (Wu et al., 2004; Costa et al., 2009; Menesatti et al., 2014; Pallottino et al., 2015).

## 2. Materials and methods

This study was carried out in 3 phases:

– training with system calibration through stereovision analysis of known artificial objects;

– testing with measurements of standing tree diameters and heights acquired through stereovision system, laser range finding (height) and tree calliper (diameter) and comparisons with direct measurements with felled trees;

– field testing of application (in natural and urban forests using the stereovision system).

In addition, during this last phase, an Android mobile application was developed for georeferencing the stereo images and manage the additional information.

### *2.1 Stereovision hardware and software*

The stereovision system consists of two high resolution SLR cameras (Canon EOS 100D) mounted on plates, locked in a known position on a bar, provided with an anti-deformation rail system, and horizontal pan adjustment to obtain a greater precision and superior alignment between the two cameras. The tilt angle error for repeated camera positioning was < 0.001°. The two camera distances were adopted: 518 mm used for the measurements of the trees diameters and 1479 mm used for height measurement (Fig. 1). The exposure mode of the two cameras exposure was set to automatic mode and without flash use to allow the exposure to adapt to different lighting conditions. During preliminary testing, the two stereo images were checked to verify that the exposure values were identical despite the slightly different scenes acquired.

One of the main problems concerning stereovision regards the synchronism in the acquisition of the images pair, especially for moving objects. Therefore, was developed a device for synchronised shooting between the two cameras based on the open-source computer board Arduino (Board model NANO v3.3; Fig. 2). This device guarantees synchronism with a negligible margin of difference of about 35 ms.

*2.2 Data collection*

The training phase consisted in measuring known distance on reference objects. Two kinds of objects were used: a T shape 3 m bars with 250 mm markers, and distances among landmarks measured on buildings (recorded with a laser meter; from 3 to 5 m). A total of 162, for the 1479 mm camera distance, and of 384, for the 518 mm camera distance, measures were recorded to calibrate the system. Sensors were positioned at a distance from the object ranging from 1 to 30 m.

Field testing was carried out at CREA in Monterotondo, Rome, Italy. The testing phase consists in measuring heights (poplars) and diameters (poplars, limes, firs, chestnut) of standing trees using the stereovision system, the traditional laser rangefinder (for heights) and the tree calliper (for diameters) on the same standing trees. Afterwards, these images were compared with the data collected directly from felled trees. Repeated measurements using different trained operators were carried out using the laser rangefinder and the tree calliper. A total of 194 tree heights and 50 breast height tree diameters were collected. The reference measurements for both height and diameter were considered to be those from the felled trees. The “reference” diameters were obtained considering the mean diameter measured using at least 3 replicates using the tree calliper. Thus, the errors of the two systems used for height (laser rangefinder and stereovision), and the stereovision used for diameter, were calculated using the felled trees as reference using:

$$\%Error = \frac{Measurement - Reference}{Reference} \cdot 100 \quad (1)$$

The operator error (Pallottino et al., 2015) was evaluated by considering the variability in the measurements taken by different operators on the same tree, for laser rangefinder (height) and tree calliper (diameter), using:

$$\%\ \text{Operator error} = \sum_{j=1}^{3}\left(1-\frac{\overline{X_j}}{\overline{X_j}+SD_j}\right)\cdot 100 \quad (2)$$

where $\overline{X}_j$ is the average repeated measurement of j$^{th}$ tree, $SD_j$ is the standard deviation of average repeated measures of j$^{th}$ tree and j is the number of trees with repeated measurements.

During the field testing of the application a total of 194 image pairs were obtained using the stereovision system, of which 50 were from woodland near Serra San Bruno, Calabria, Italy and 144 were from urban parks in Rome, Italy.

*2.3 Triangulation and measurement software*

Specific software was designed to extract the distances between two points within stereo images through a triangulation method. The software, implemented in the Matlab (rel 7.1; Mathworks, Natick, Mass., USA) environment. A trained operator manually identified, on each stereo image, two points describing height or diameter (i.e. landmarks) and the software automatically returns the required measurement. The software could also extract of angles based on 3 landmarks on the two stereo images.

*2.4 Georeferencing web application*

An *ad hoc* georeferencing web application was developed for the stereo images data management and the introduction of geographic and additional information. The system, called infotracing (Costa et al., 2013), consists of an application (designated SmartTree) developed for the Android OS platform. This application allows for image acquisition using a smartphone and the storage of associated of additional information, including: information related to stereo images and GPS data for the position and species name of the tree. This information is stored on a centralised web database. The data on the database could be inserted or queried from different devices. Users could be technical (i.e. forestry) operators conducting field operations, policy managers, inspectors, forest technicians and also generic users. The SmartTree application can work autonomously in an off-line mode, not synchronised with the web-database, or as a field digital data collector for distributed surveys synchronised with the web-database. In this second mode, the application becomes the software interface layer of a shared workflow established between the users to manage the data archived in the web database.

The web-database runs on a server which provides a web-site application (SmartTree-Web) to allow access from desktop terminals. The web application allows users to query and manage the collected data with the proper security policies. The application also provides specific geographic functionality for data analysis. The web application architecture is based on a classic client-server scheme and has been developed using open-source technology. The client application runs on a standard web browser and is implemented in JavaScript using Geo-Ext, an Ext-JS framework extension focused on geographical data visualisation and editing. The client application has the appearance of a desktop application with tabular data, detail views and geographical map rendering. The client application does not store data on the user's personal computer. All the data are provided by a server application implemented in PHP and are stored in a web-database implemented in MySQL with a geographical extension. The data needed by the client application are requested by the server application to the database and are returned through the internet connection to the client application.

The GPS information is acquired manually through the smartphone antenna with an accuracy approximately equal to 5 m. Once the tree reference image is acquired and stored, the operator needs to move as close as possible to the tree to acquire the tree coordinates. The GPS coordinates, relative to the stereo-images pair, are registered within the picture taken by the smartphone, according to the specifications of Exchangeable image file format (Exif), and consequently extracted. In time it is hoped that the GPS location accuracy will increase consistently due to the diffusion of L5 GNSS satellites characteristics and the capability of the smartphone chipset to lock first onto the satellite with the L1 signal from satellites, and then to refine it with the L5. This is much less prone to distortions from multipath reflections than L1 (Svaton, 2015).

The acquired stereo images are archived and georeferenced creating a KML file for sharing and disseminating along with all the additional information manually inserted by the operator. The KML file was chosen as the interchange file format because it has been adopted by various software platforms in order to eliminate problems while sharing information. Such files can be viewed through both, Google Maps and Google Earth. The KML file was written using a dedicated utility in Java which elaborates the images acquired by the SmartTree application, including the extraction of all the information manually inserted by the operator. It then extracts the GPS position (latitude and longitude) from the smartphone JPG (Exif) creating a CSV file. This CSV file contains all the info of each single image with references to stereo-visual images acquired from SLR cameras. Subsequently the software generates the KML file containing: the single image, the position, the species and the notes, adapting them graphically according to the scheme of KML file.

The KML file can be easily converted in a JSON structure and can be imported in the web-database to archive all the data collected by the application.

The application is not yet available via Google since it is a prototype developed in the specific context of the research projects reported here.

## 3. Results

*3.1 Training phase*

Figure 3A shows a scatter plot for the average percentage error between the observed and estimated readings for the stereovision algorithm, during training performed on 162 objects of known measurement (from 100 mm to 4500 mm placed at distances from 5 to 30 m) with focal length set at 18 mm and sensor distance was 1479 mm. The average percentage error resulted was 1.76 ± 1.33%. Figure 3B shows the same results but for the calibration performed on 384 objects and with a sensor distance equal to 518 mm. For this phase the average percentage error was 0.93±1.12%. Since this distance between sensors is used only with small and close objects (i.e. trees diameters), this effect is negligible.

*3.2 Testing phase*

The operator error (%) was 6.5 ± 4.5% for the measurements of heights with laser rangefinder and to 1.8±1.7% for the measurements of diameters with the tree calliper for a total of 50 trees used for each .

Figure 4 shows the scatter plots of the differences between the reference measurements and these measured with the stereovisions in the testing phase. Figure 4A shows a scatter plot of the differences between the 50 observed heights (reference) and the heights measured with the laser rangefinder; the measurement error was equal to 6.8±6.6%. There were no significant differences between the two systems (t test $p > 0.05$). Figure 4B shows the scatter plot of the differences between the 50 observed heights (reference) and the heights measured with the stereovision. The measurement error was equal to 5.8±5.5%. There were no significant differences between the two systems (t test $p > 0.05$). Figure 4C shows the scatter plot of the differences between the 60 observed diameters (reference) and the diameters measured with the stereovision. The measurement error was equal to 4.2±3.0%. There were no significant differences between the two methodologies (t test $p > 0.05$).

*3.3 In-field testing phase*

Figure 5 shows screen images from the SmartTree application developed in this study for the georeferencing and management of the stereo images developed in the research projects reported here. Through this application, 50 surveys in Calabria and 144 in Rome of georeferenced images were established with the stereovision system. The set of images were processed following capture and exported in KML format as reported earlier.

## 4. Discussion

Timely and accurate measurements of vegetation structure are increasingly needed across large areas to support a wide range of activities related to sustainable forest and urban green space management (Rosenqvist et al., 2003). This study deals with the setup of a smart stereovision system for estimating dendrometry parameters (height and diameter), georeferencing the relative information and the management of stereo images using a specifically developed application that is available in the field.

The stereovision system, being unable to process the data in real time, can optimise the data acquisition. The main limit to the use of the system is imposed by the visual field. It gives the possibility to estimate parameters without the need to fell the trees and the application can produce biomass estimates based on a single stereo images pair. As previously mentioned, remote sensing based applications (such as LIDAR) represent a resource to measure vegetation structure across large areas. However, critical to the adoption of LIDAR as a survey tool, is the capacity to simultaneously measure in detail and with high accuracy both, vertical and horizontal vegetative structure as well as terrain morphology (Wulder et al., 2012). In addition, because the spatial extent and spatial resolution of a given sensor are inversely related (Franklin et al., 2002) the characterisations of large areas of vegetation using remote sensing tools often have sub-optimal precision for many applications (Xie et al., 2008).

The tools proposed here are particularly useful for urban green applications, given the possibility to georeference image acquisitions through the mobile device and insert additional information such as, for example, tree health status. Moreover, the stereovision system has the possibility of totally surveying the plant, and of measuring the distances and angles, and this could be used to analyse and classify the state of mechanical danger represented by each tree toppling or otherwise failing.

In forests, acquisition of multiple dendrometry parameters is needed, and, even if it becomes difficult to frame the entire plant (information on the height of the individual), the system can be useful to support measurements of basal area using the relascope (Bitterlich, 1984). In fact, from the readings of the diameters it is possible to derive other population statistics such as population size and the diameter class distribution. With repeated measures over time, accurate diameter estimation provided by stereo-vision could allow other important parameters related to the timber growth to be determined. Moreover, using the same information integrating the dendrometry measurements and the leaf area index (LAI; Chianucci et al., 2015) and knowing the age of the tree population it could be possible to estimate the health status of the trees and establish the level of soil fertility. The same technology could be further applied for the evaluation of forestry vehicles transit inside wooded areas.

The “user friendly” information provided could be used by a field operative, as well as by a trained technician. In fact, a member of the public with this application, could both actively provide information as well as receive it. In this way, a public institution would already have a data base of trees at risk of failure to commission a technician to perform a visual tree assessment (VTA) analysis. The use of such technology could improve profitability and help foresters make economic and environmental management decisions for treatment of individual trees and forest stands, improve thinning and harvesting operations and efficiently allocating timber resources for optimal utilisation (Proto et al., 2017).

## 5. Conclusions

The proposed system allows dendrometry information to be acquired with an error comparable to the one of the devices used. The information can be georeferenced with using web-based application (SmartTree). The system can be considered as a valid tool but with some limitations due, for example, to the poor woodland management, low usability in coppices and the impossibility of estimating heights in the presence of dense vegetation. Because the two cameras were set to the automatic exposure mode, the resulting images were adapted to varying lighting conditions acquired. However, the possibility of optimising the acquisition times in the forest, for example by the estimation of diameters, allows the number of observations to be increase and giving better approximations than traditionally methods using manual measurement that are also subject errors or to the relascope. Finally, the application of the proposed technology has the possibility to use the dendrometry data acquired by the georeferencing and the positioning of the forest plants with the ultimate aim of geolocating the wood mass present in the examined area.

## 6 Acknowledgements

Some activities in this study were funded by the Italian Ministry of University and scientific research (MIUR), as part of the project "Ambi.tec.Fil.Legno" (PON03PE_00024_1) and by the project AGROENER (D.D. n. 26329) funded by the Italian Ministry of Agriculture (MiPAAF); some other has been funded by Regione Lazio FILAS, project URBANFOR3. Authors would like to thank Matteo Viscardi and Tullio Guglielmelli of University of Tuscia of Viterbo, and the personnel of CREA-IT Dr. Marcello Biocca, Dr. Andrea Acampora, Dr. Giuseppina Di Loreto, and for their support in the field operations Sandu Lazar and Franco Bernardini. All the authors equally contribute to the writing of the paper and to its content.

## 7 References


Bai, X. B., Wang, K. Q., & Wang, H. (2005). Research on the classification of wood texture based on Gray Level Co-occurrence Matrix [J]. *Journal of Harbin Institute of Technology*, *12*, 021.

Bitterlich, W. (1984). The Relascope idea: relative measurements in forestry. *Commonwealth Agricultural Bureaux, Farnham Royal (Slough)*. England, (242 pp.).

Brownlie, R. K., Carson, W. W., Firth, J. G., & Goulding, C. J. (2007). Image-based dendrometry system for standing trees. *New Zealand Journal of Forestry Science*, *37*(2), 153.

Chasmer, L., Hopkinson, C., & Treitz, P. (2006). Investigating laser pulse penetration through a conifer canopy by integrating airborne and terrestrial lidar data. *Canadian Journal of Remote Sensing*, *32*, 116-125.

Chianucci, F., & Cutini, A. (2013). Estimation of canopy properties in deciduous forests with digital hemispherical and cover photography. *Agricultural and Forest Meteorology*, *168*, 130-139.

Chianucci, F., Puletti, N., Giacomello, E., Cutini, A., & Corona, P. (2015). Estimation of leaf area index in isolated trees with digital photography and its application to urban forestry. *Urban Forestry & Urban Greening*, *14*(2), 377-382.

Clawges, R., Vierling, L., Calhoon, M., & Toomey, M. (2007). Use of a ground-based scanning lidar for estimation of biophysical properties of western larch (*Larix occidentalis*). *International Journal of Remote Sensing*, *28*, 4331-4344.

Costa, C., Scardi, M., Vitalini, V., & Cataudella, S. (2009). A dual camera system for counting and sizing Northern Bluefin Tuna (*Thunnus thynnus*; Linnaeus, 1758) stock, during transfer to aquaculture cages, with a semi automatic Artificial Neural Network tool. *Aquaculture*, *291*(3-4), 161-167.

Costa, C., Antonucci, F., Pallottino, F., Aguzzi, J., Sarri, D., & Menesatti, P. (2013). A review on agri-food supply chain traceability by means of RFID technology. *Food and Bioprocess Technology*, *6*, 353-366.

Dahl, A. B., Guo, M., & Madsen, K. H. (2006). Scale-space and watershed segmentation for detection of wood logs. In: *Vision Day, Informatics and Mathematical Modelling*.

Fink, F. (2004). Foto-optische erfassung der dimension von nadelrundholzabschnitten unter einsatz digitaler bildverarbeitender methoden. Dissertation, Fakultaet fuer Forst- und Umweltwissenschaften der Albert-Ludwigs-Universitaet Freiburg i. Brsg.

Firth, J. G., Brownlie, R. K., & Carson, W. W. (2000). Accurate stem measurements key to new image-based system. *New Zealand Journal of Forestry*, *45*, 25-29.

Franklin, S. E., Lavigne, M. B., Wulder, M. A., & Stenhouse, G. B. (2002). Change detection and landscape structure mapping using remote sensing. *The Forestry Chronicle*, *78*, 618-625.

Gobakken, T., & Næsset, E. (2004). Estimation of diameter and basal area distributions in coniferous forest by means of airborne laser scanner data. *Scandinavian Journal of Forest Research*, *19*(6), 529-542.

Gutzeit, E. &Voskamp, J. (2012). Automatic segmentation of wood logs by combining detection and segmentation. In *International Symposium on Visual Computing* (pp. 252-261). Springer, Berlin, Heidelberg.

Hauglin, M., Lien, V., Næsset, E., & Gobakken, T. (2014). Geo-referencing forest field plots by co-registration of terrestrial and airborne laser scanning data. *International journal of remote sensing*, *35*(9), 3135-3149.

Herrera, P. J., Pajares, G., Guijarro, M., Ruz, J. J., & Cruz, J. M. (2011). A stereovision matching strategy for images captured with fish-eye lenses in forest environments. *Sensors*, *11*(2), 1756-1783.

Kerr, J. T., & Ostrovsky, M. (2003). Fromspace to species: Ecological applications for remote sensing. *Trends in Ecology & Evolution*, *18*, 299-314.

Lefsky, M. A., Cohen, W. B., Parker, G. G., & Harding, D. J. (2002). Lidar remote sensing for ecosystem studies. *BioScience*, *52*, 19-30.

Menesatti, P., Costa, C., Antonucci, F., Steri, R., Pallottino, F., & Catillo, G. (2014). A low-cost stereovision system to estimate size and weight of live sheep. *Computers and Electronics in Agriculture*, *103*, 33-38.

Pallottino, F., Steri, R., Menesatti, P., Antonucci, F., Costa, C., Figorilli, S., & Catillo, G. (2015). Comparison between manual and stereovision body traits measurements of Lipizzan horses. *Computers and Electronics in Agriculture*, *118*, 408-413.

Proto, A.R., Macrì, G., Bernardini, V., Russo, D., & Zimbalatti, G. (2017). Acoustic evaluation of wood quality with a non-destructive method in standing trees: a first survey in Italy. *iForest-Biogeosciences and Forestry*, *10*(4), 700-706.

Rosenqvist, A., Milne, A., Lucas, R., Imhoff, M., & Dobson, C. (2003). A review of remote sensing technology in support of the Kyoto protocol. *Environmental Science & Policy*, *6*, 441-455.

Seavy, N. E., Viers, J. H., & Wood, J. K. (2009). Riparian bird response to vegetation structure: a multiscale analysis using LiDAR measurements of canopy height. *Ecological Applications, 19*(7), 1848-1857.

Simonse, M., Aschoff, T., Spiecker, H., & Thies, M. (2003). Automatic determination of forest inventory parameters using terrestrial laser scanning. In: Proceedings of the scandlaser scientific workshop on airborne laser scanning of forests. Vol. 2003, pp. 252-258.

Smiley, E. T., Fraedrich, B. R., & Fengler, P. (2007). Hazard tree inspection, evaluation, and management. In: *Urban and Community Forestry in the Northeast*. Springer, Dordrecht, (pp. 277-294).

Svaton, J. (2015). Experimental reception of new GNSS signals. *2015 International Association of Institutes of Navigation World Congress (IAIN)*, pp. 1-4.

Wu, J., Tillett, R., McFarlane, N., Ju, X., Siebert, J. P., & Schofield, P. (2004). Extracting the three-dimensional shape of live pigs using stereo photogrammetry. *Comp. Electron. Agric.*, *44*, 203-222.

Wulder, M. A., White, J. C., Nelson, R. F., Næsset, E., Ørka, H. O., Coops, N. C., Hilker, T., Bater, C. W., & Gobakken, T. (2012). Lidar sampling for large-area forest characterization: A review. *Remote Sensing of Environment*, *121*, 196-209.

Xie, Y., Sha, Z. & Yu, M. (2008). Remote sensing imagery in vegetation mapping: A review. *Journal of Plant Ecology*, *1*, 9-23.

**Figure captions**

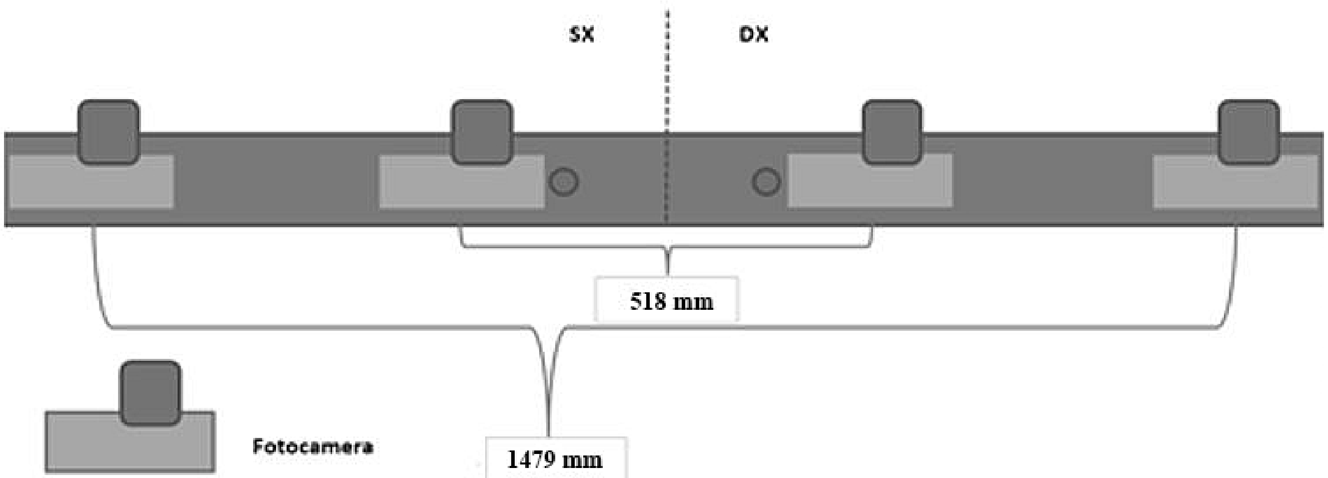
Fig. 1: Stereovision system consisting of two high resolution SLR cameras (Canon EOS 100D) mounted on plates positioned on stiff rails and with horizontal tilt adjustment.

Fig. 2: Device for simultaneous shooting control over the two high resolution SLR cameras (Canon EOS 100D) developed with an open source (Arduino) technology.

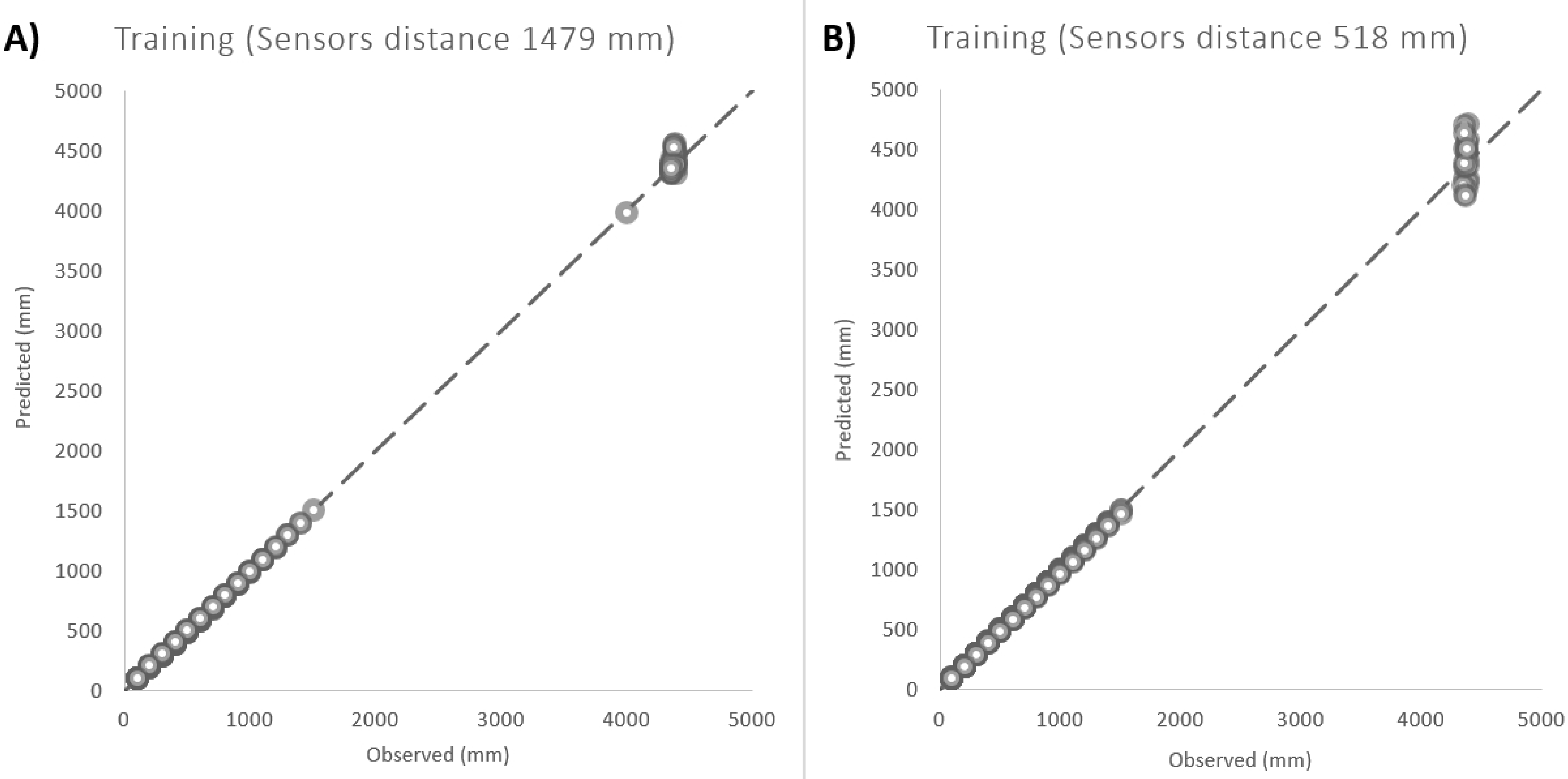
Fig. 3: Scatter plots for the estimation of the average percentage error between the observed and estimated measurements by the stereovision algorithm, during training performed on 162 (A) and on 384 (B) objects of known measurement (from 100 mm to 4500 mm placed at distances from 5 to 30 m) with focal length set at 18 mm and sensor distance equal to 1479 mm (A) and 518 mm (B).

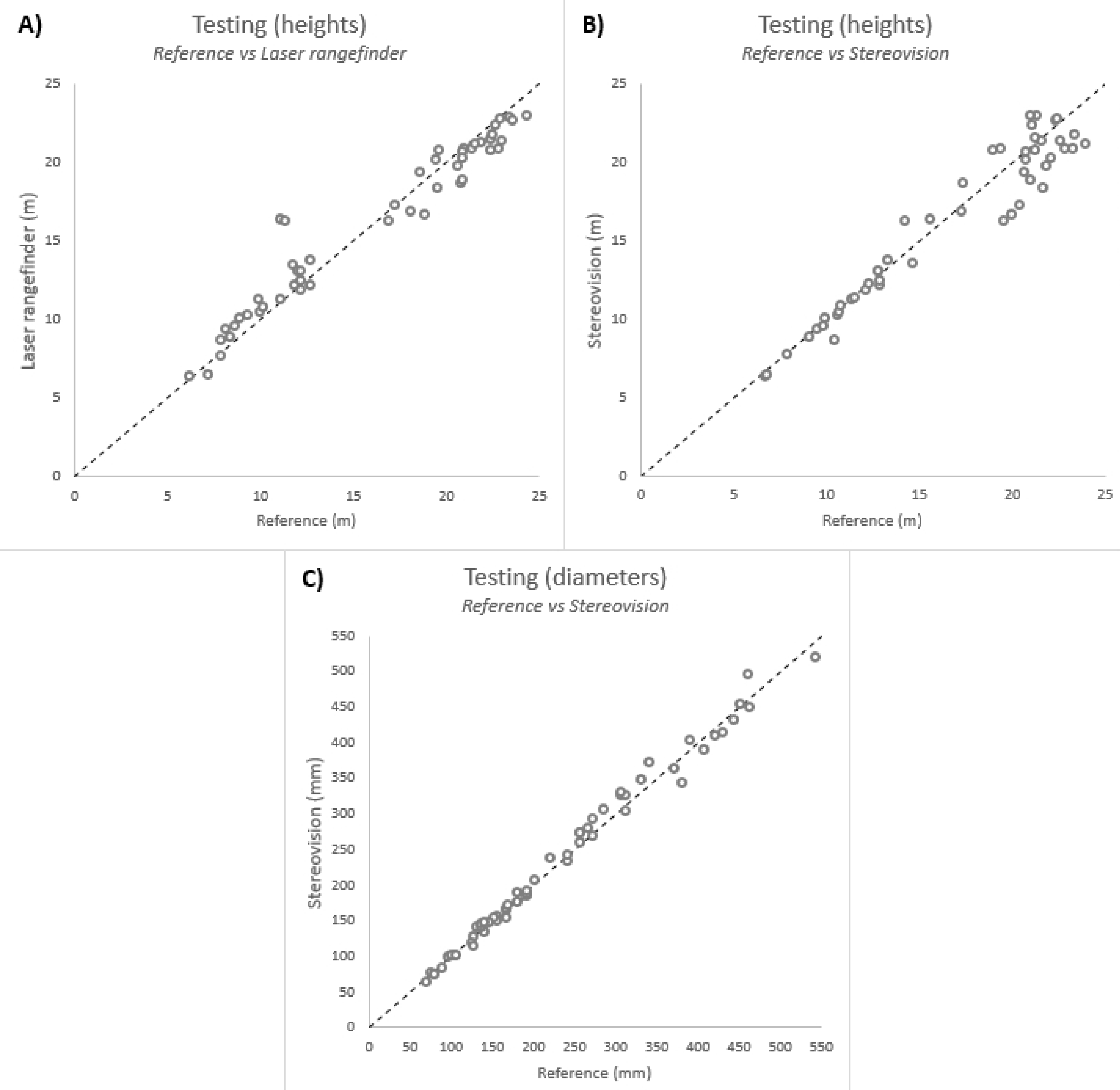
Fig. 4: Scatters plots of the testing phase. A) scatter plot of the differences between the 50 observed heights (reference) and the heights measured with the laser rangefinder; the measurement error was equal to 6.8±6.6%; B) scatter plot of the differences between the 50 observed heights (reference) and the heights measured with the stereovision.

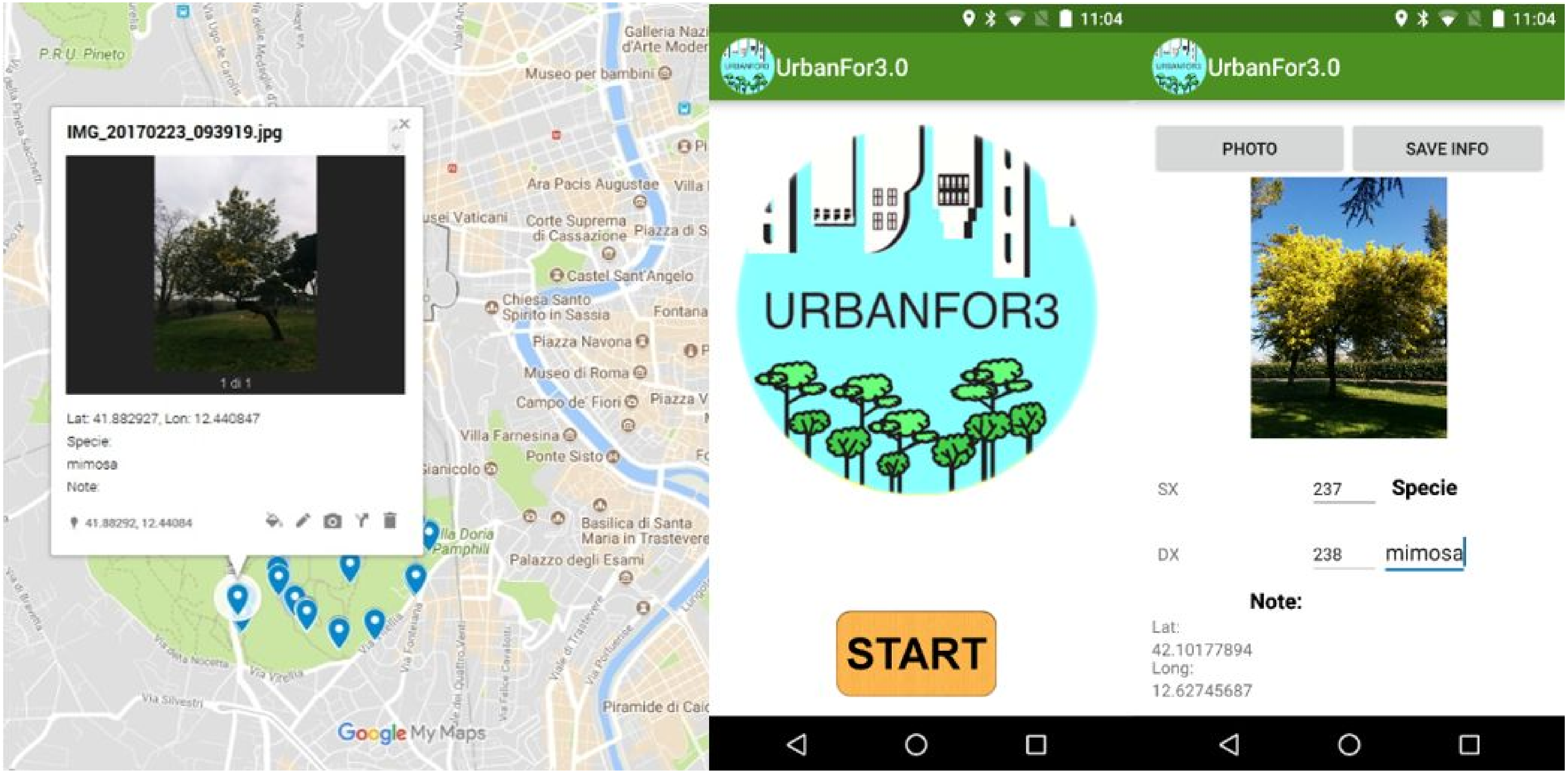
Fig. 5: Screen images from the SmartTree application developed in this study for georeferencing and management of stereo images.


SX
DX
518 mm
1479 mm
Fotocamera


Shooting
Focus
Selector for continuous shooting and laying B (Bulb)


A)
Training (Sensors distance 1479 mm)
Predicted (mm)
Observed (mm)
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
0
1000
2000
3000
4000
5000
B)
Training (Sensors distance 518 mm)
Predicted (mm)
Observed (mm)
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
0
1000
2000
3000
4000
5000


A)
Testing (heights)
Reference vs Laser rangefinder
Laser rangefinder (m)
Reference (m)
0
5
10
15
20
25
B)
Testing (heights)
Reference vs Stereovision
Stereovision (m)
Reference (m)
C)
Testing (diameters)
Reference vs Stereovision
Stereovision (mm)
Reference (mm)
0
50
100
150
200
250
300
350
400
450
500
550


IMG_20170223_093919.jpg
1 di 1
Lat: 41.882927, Lon: 12.440847
Specie:
mimosa
Note:
41.88292, 12.44084
P.R.U. Pineto
Galleria Nazi
d'Arte Moder
Museo per bambini
Ara Pacis Augustae
Musei Vaticani
Corte Suprema
di Cassazione
Castel Sant'Angelo
Chiesa Santo
Spirito in Sassia
Piazza Navona
Museo di Roma
Campo de' Fiori
Villa Farnesina
Ponte Sisto
Gianicolo
Villa Doria
Pamphili
Basilica di Santa
Maria in Trastevere
Palazzo degli Esami
Piramide di Caio
Google My Maps
11:04
UrbanFor3.0
URBANFOR3
START
11:04
UrbanFor3.0
PHOTO
SAVE INFO
SX
237
Specie
DX
238
mimosa
Note:
Lat:
42.10177894
Long:
12.62745687