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A community-based urban forest inventory using online mapping services and consumer-grade digital images

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ABSTRACT

Community involvement in gathering and submitting spatially referenced data via web mapping applications has recently been gaining momentum. Urban forest inventory data analyzed by programs such as the i-Tree ECO inventory method is a good candidate for such an approach. In this research, we tested the feasibility of using spatially referenced data gathered and submitted by non-professional individuals through a web application to augment urban forest inventory data. We examined the use of close range photogrammetry solutions of images taken by consumer-grade cameras to extract quantitative metric information such as crown diameter, tree heights and trunk diameters. Several tests were performed to evaluate the accuracy of the photogrammetric solutions and to examine their use in addition to existing aerial image data to supplement or partially substitute for standard i-Tree ECO field measurements.

Digital images of three sample sites were acquired using different consumer-grade cameras. Several photogrammetric solutions were performed using the acquired image sets. Each model was carried out using a relative orientation process followed by baseline model scaling. Several distances obtained through this solution were compared to the corresponding distances obtained through direct measurements in order to assess the quality of the model scaling approach. Measured i-Tree ECO field plot inventory data, online aerial image measurements and photogrammetric observations were compared. The results demonstrate the potential for using aerial image digitizing in addition to ground images to assist in participatory urban forest inventory efforts.

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1. Introduction

Urbanization is increasing as the human population expands and people become more mobile. As a result, many areas experience some degree of urbanization. The importance of natural resources has become more accepted and is being integrated into the planning and decision-making processes of many municipalities, government agencies and land owners. Citizens have become more aware of the fundamental relationships between human society, geography and natural resources (Nowak et al., 2001). Associated with this awareness has come the desire to gain more knowledge and be more involved in the planning and decision-making processes. This desire has brought about the question of whether or not concerned participants can, with minimal instruction and readily available equipment, be utilized as sources for gathering data and geospatial information in an accurate and assessable manner (Goodchild, 2007). In this context, we envision members of local or regional outreach environmental groups such as the Florida Master Gardeners, Master Naturalists, or Tampa Bay urban forest groups to participate in collecting information about pre-specified urban forest plots. This may be even feasible for some of the groups that require their members to achieve certain number of annual volunteering hours.

The usefulness of individuals without specialized training to gather quality data could prove invaluable and greatly expand much needed natural resource inventories (Bloniarz and Ryan, 1996). Inventories of our natural resources are vital in understanding the distribution and structure of flora in urban areas, the spread and distribution of invasive species, and the services urban plant communities are providing. Without comprehensive and repeated inventories of our natural resources it is impossible to rigorously examine the impacts our society has on these resources, as well as their impact on us.

Since online delivery of geospatial information has successfully evolved, there is great potential for the data collection processes to achieve a similar level of widespread accessibility. The evo-

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lution of sensing and communication technologies has brought readily accessible web-top applications and mobile devices into the hands of many citizens. The ease with which most people can use these modern devices and programs allows individuals to navigate through data that could have been considered inaccessible or unexpected before.

Accessibility has evolved in the areas of presenting and manipulating geospatial data toward a broader user base. However, data collection remains largely in the hands of geospatial experts, researchers and other trained specialists. There have been some rudimentary investigations into the possibility of community-driven geospatial data collection. As a whole, however, the data collection process is still expensive, time-consuming and by necessity requires rigorous review and quality considerations. Often, data must be aggregated from a wide variety of resources such as field-survey technicians or remote sensing methods. This process is inherently complex and generally feasible only to centrally organized and expertly trained professionals. Goodchild (2007) indicated that advances in web mapping services and the availability of high resolution aerial and satellite images add a spatial dimension to the knowledge exchange process and facilitate community-based spatial data sharing and collection. This type of data can provide continuous updates to existing inventories, increasing their robustness and facilitate the creation of new inventories for previously un-sampled locations.

Urban forest inventories are a valuable asset to planners and decision makers and can provide needed information about the quality, quantity and location of natural resources in urban areas. Urban forest functional models such as i-Tree ECO (e.g. Urban FORest Effect model – UFORE) (Eco User Manual, 2009) are used to analyze tree coverage, species diversity, invasive species counts, carbon sequestration and many other aspects of the urban forest. The models used in these applications depend on field data collection and require significant resources such as qualified personnel and adequate equipment (Eco User Manual, 2009). These models analyze the tree-dominated vegetation resource as one component of an urban ecosystem and do so at the landscape scale. The need to incorporate local-scale urban forest inventory into urban forest structure quantification was clearly demonstrated by Escobedo and Nowak (2009) in their assessment of local-scale urban forest ecosystem services. One method to accomplish this is to increase the amount of data collected by citizens and subsequently input these into analyses.

There have been recent projects that allow communities to input their localized and spatially referenced information (BioMapping, 2007; WorldWater, 2009; SE-EEPC, 2008). Most of these projects were concerned with referencing non-spatial information to a single location and/or utilized sophisticated equipment to collect the data. Generally, they were not designed to gather extensive quantitative spatial information and many seemed to lack methods for quality control and assessment of collected data. Many of the drawbacks and uncertainties in community-driven data collection procedures may be accommodated through careful implementation design (e.g. targeting pre-specified site locations within certain time frame). The quantitative and qualitative data extracted from the images can enrich existing data repositories and improve the data quality control procedures.

Historically, analog and digital images provided an efficient tool to exchange qualitative information. Images were analyzed manually or automatically for applications such as disease diagnosis and crime scene investigation. With their wide availability and ease-of-use, low-cost consumer-grade digital cameras could be a turning point toward better and wider-scale utilization of community-based data. Some researchers have tested the use of photogrammetric tools to derive accurate metric information from digital images that were captured with consumer-grade digital cameras (Girelli et al., 2005; Habib et al., 2004; Arias et al., 2005). Although some researchers questioned the component quality and internal stability of consumer-grade cameras (Labe and Forstner, 2004; Granshaw, 1980; Fraser, 1997), which can degrade the accuracy for some mapping applications, we hypothesize that measurements extracted from images captured using this type of camera is adequate for many natural resources inventory applications.

The driving impetus for the development of this research project has been the idea that the potential for community-based gathering of quantitative urban forest information has been undermined and rarely explored. One of the objectives of this research is to examine the validity of an alternative approach that involves citizens in the data collection process by taking advantage of online web mapping services and communication technologies. We tested the use of ground images taken with consumer-grade digital cameras to provide i-Tree ECO-style urban forest inventory and sampling data. We analyzed the use of a photogrammetric solution using surveyed control points, check points and distances. Finally, we examined the validity of using a photogrammetric solution in addition to widely available online aerial images for capturing the allometric information necessary for the i-Tree ECO urban forest inventory program.

2. Urban Forest Inventory Web Application development

The Urban Forest Inventory Web Application (UFIA) was developed by our team and hosted on the University of Florida's Institute of Food and Agricultural Science's (UF-IFAS) web server. A detailed description of the application development and functionalities can be found in Thornhill et al. (2009). The application utilized Google Maps™ (Google Maps, 2009) graphical interface to provide the spatial referencing capability for the input of information on the plot and tree levels. It allows registered users to add or edit urban forest inventory plots and to input spatially referenced flora information related to these sites in a multi-step work flow. Fig. 1 shows a screen snapshot of the tree data entry page.

In addition to inputting spatially referenced information about individual plants in a plot, users are allowed to upload images into the database. Our goal is to use these images in a photogrammetric solution to provide additional or redundant information for the urban forest inventory. To be able to successfully solve a photogrammetric model, users are asked to enter distances between chosen reference points that are visible in the images. These distances are used to scale the photogrammetric model and to check the solution's accuracy. Users are also asked to roughly locate the camera position for each image taken. Plant and camera locations are interactively input by mouse clicks with the aid of Google Maps™ aerial image background. Users are advised on the techniques and best practices to take the images so that we achieve a robust photogrammetric solution.

3. Testing the photogrammetric solutions

Close range photogrammetric solutions (Wolf and Dewitt, 2000) have been used in architectural modeling (Debevec et al., 1998; Yastikli, 2007), crash scene analyses (Fraser et al., 2008; Xinguang et al., 2009), and digital surface model creation (Abd-Elrahman and Gad-Elraab, 2008; Rieke-Zapp and Nearing, 2005). A typical photogrammetric job is preceded by a camera calibration process to estimate the camera's interior orientation parameters. There is a wealth of literature on the topic of camera calibration, including those involving low-cost digital cameras (Labe and Forstner, 2004; Chandler et al., 2005; Remondino and Fraser, 2006). Self-calibration bundle adjustment has also been used to simultaneously solve for

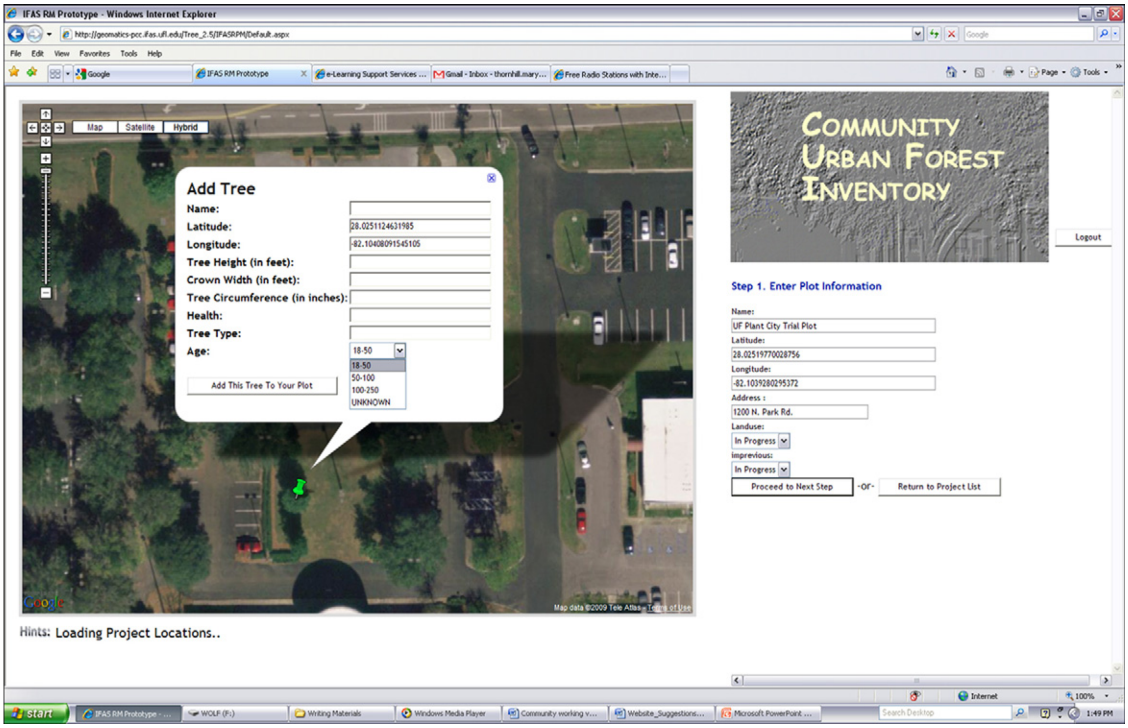

Fig. 1. UFIA application plant entry page.

a camera's interior and exterior orientation parameters (Atkinson, 1996; Triggs, 1997). A successful bundle adjustment solution of a set of overlapping images can theoretically be achieved if sufficient well-distributed features are available in the overlap area of the images. Although, much research proved the success of the self-calibration bundle adjustment, some cases demonstrated that a robust solution is not guaranteed, especially due to the geometry of the image set (Remondino and Fraser, 2006). The majority of these tests were conducted using professional targets or corners of man-made features (e.g. buildings) as control points.

Our objective of testing the use of consumer-grade digital cameras to capture quantitative information in order to substitute for or complement urban forest inventory efforts is subject to the same type of debate on the validity of the photogrammetric solution. This argument is even more evident when considering our proposal to utilize images acquired by volunteer community members for areas rich in natural features. We carried out our test for the validity of the photogrammetric solution in two different phases. The first phase focused on determining the absolute accuracy of the photogrammetric model. For this phase, we used images taken by our team with a high-end consumer-grade digital camera for an i-Tree ECO plot. We selected points on the plot to survey using a calibrated Leica TCR405 total station. With a five-second standard deviation of angle measurements and (2 mm + 2 mm/km) distance measurement accuracy, the expected positional accuracy for each control point should not exceed one centimeter. Some of these points were integrated as control points in the photogrammetric solution, while the rest were reserved to check the accuracy of solution results.

The second phase of our test was concerned with the photogrammetric solution in the case of images uploaded by community participants. In this case, only distances between marked points in the plot were used. A relative orientation process was conducted using several manually selected tie points common in the images. The model formed by the relatively oriented images was scaled to real world dimensions using a single baseline length. This baseline represents the field distance measured by a community participant between two different points. Each one of these points should appear in the overlap area of at least two images. This technique represents the case of a participant uploading site-specific images, to solve the photogrammetric model, and distance(s) measured in the field between marked points, to scale the model to real world dimensions.

All photogrammetric solutions were achieved through the PhotoModeler™, a low-cost commercial photogrammetry software (PhotoModeler, 2009). We started with three images and added more images gradually. The processing time for the photogrammetric models tested in this research (6–12 images each) was 4–8 h per model. This processing time is comparable to the time taken by a crew to travel to a site and collect the measurements, especially if site locations are spatially spread. Experiments showed some variations in processing time due to operator errors, camera characteristics and geometry weakness. We also experienced a reduction in the processing time with repeated processing of different sets of images taken to the same site mainly due to increased operator familiarity with the site. All encountered complications were overcome by reviewing selected point locations and adding more points to strengthen the geometry. In order to strengthen the geometry it was necessary to use tie points that were located on natural objects in the images such as leaves on a tree or discolored areas on a tree bark as shown in Fig. 2. Relying only on built-up objects, such as building corners, to provide enough geometrical constraints to solve the photogrammetric model was not possible since the building and nearly all other man-made objects were located in one portion of the imaged area, which could not provide enough geometrical constraints to solve the photogrammetric model.

3.1. Photogrammetric solution using surveyed control points

To determine the accuracy of the bundle adjustment solution using images captured by a consumer-grade camera and surveyed control points in an urban forest inventory site, a high-end

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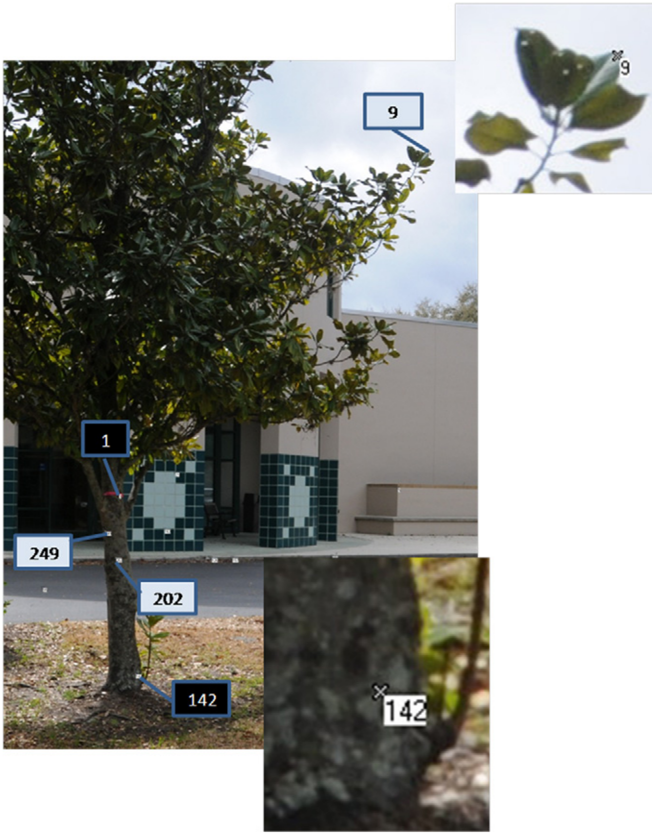

Fig. 2. Example of natural objects used as tie points to strengthen model geometry.

consumer-grade Nikon D300 camera equipped with a Nikkor DX AF-S 18–250 mm lens was used to take a set of 12 images. The camera and lens were set to manual mode and the lens was fixed to prevent accidental changes in the settings during the image acquisition process. A total of 15 points in the scene were surveyed using a calibrated 5-s Leica TCR405 total station (Leica, 2009) from a single location. The points were surveyed either in a prism-less mode or using a paper reflector, with point accessibility being the main factor in determining the surveying mode. Fig. 3 shows one of the acquired images with some of the control (surveyed) points and tie points used.

Table 1
Difference in check point coordinates obtained using the photogrammetric solution and the traditional ground surveying techniques.

Point ID	ΔX (cm)	ΔY (cm)	ΔZ (cm)	Total error (cm)
53	0.2	−2.0	9.0	9.2
77	1.5	−6.3	0.0	6.5
126	−1.2	−6.0	−1.0	6.2
132	1.8	−0.5	0.8	2.1
142	1.0	3.0	−1.9	3.7
157	−1.7	−4.9	−1.7	5.4
163	−1.4	−5.6	−1.7	6.0
175	0.7	−5.1	−1.3	5.3
				Average error
RMSE	1.3	4.6	3.4	5.5

A self-calibration bundle adjustment solution involving 12 images was achieved. Only six of the surveyed control points were incorporated in the solution. The remaining points were left as check points. The solution converged in 10 iterations. Table 1 shows the errors in the computed check point coordinates and their associated root mean square error (RMSE) for the check points. These errors represent the differences in the coordinates obtained from the photogrammetric solution and those obtained from ground surveying. The small error values listed in the table indicates the validity of the photogrammetric solution as a substitution to the ground surveying technique. It should be mentioned here that one of the check points gave significantly higher errors than the remaining points. This point was located on a metal post that may have affected the survey accuracy. On the other hand, the point had the highest precision vector length (a measure of the expected spread of the location about its computed value) among all points in the solution. The precision vector length for this point was four times higher than the average precision vector length for all points in the solution and was thus excluded from the RMSE and the total average error values shown in Table 1.

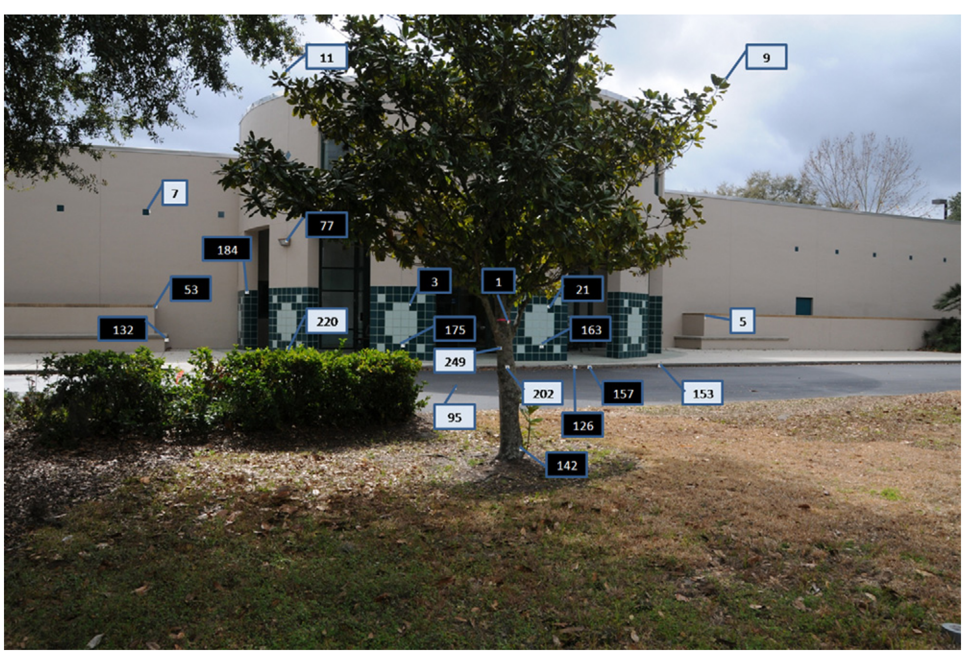

Fig. 3. Sample image showing some surveyed control/check (black boxes) points and tie (light boxes) points.

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Table 2
Difference in distances obtained through the control-assisted photogrammetric solution and the scaled model photogrammetric solution using three different scale baseline lengths.

Check line (Pt ID #s)	Check line distance (m)	Differences in check line distances (cm)		
		Model scaled with a 2.69 m baseline	Model scaled with a 17.5 m baseline	Model scaled with a 24.42 m baseline
53–184	2.67	2.2	6.2	5.3
53–147	17.5	−25.5	0.0	−5.6
3–147	24.43	−28.7	7.0	−1.0
251–247	1.16	2.3	4.1	3.7
249–251	0.21	0.4	0.7	0.6
242–247	7.49	15.5	26.8	24.3
245–247	1.48	3.0	5.2	4.7
232–228	5.17	10.8	18.6	16.9
238–9	4.34	8.7	15.2	13.8
1–184	17.36	8.9	34.7	29.0
	RMSE	14.2	16.2	14.1

3.2. Photogrammetric solution using scaled model

In a community-based data collection context, no control points will be available to solve the photogrammetric model. Only the images and the distances between marked points in the scene uploaded by the participating citizens will be available. In this case, a photogrammetric solution can be achieved in two steps. A relative orientation process is performed to estimate the camera attitude angles and the lens center locations in a model coordinate system. This relative orientation step is followed by scaling the model with one of the input distances.

In our experiment, the same tie points used in the control-assisted photogrammetric solution described in Section 3.1 were used and a self-calibration bundle adjustment solution was obtained using the PhotoModeler^{TM} software package. Three different baseline distances were used independently to test the effect of the scaling baseline length on the obtained accuracy. Baseline lengths of 2.69, 17.50 and 24.42 m were measured with a fiberglass measuring tape and used to represent relatively short, medium and long baseline distances. To test the accuracy of each of these solutions, several points were selected in the output scaled models and the distances between these points were computed and compared with the corresponding distances obtained from the control-assisted model described in Section 3.1. Table 2 lists the examined distances, the differences between the scaled model results and those resulting from the control-assisted solution and the RMSE of these differences.

3.3. Photogrammetric solution at different sites

Additional photogrammetric solutions were performed to examine the quality of the proposed method using different lower-end consumer-grade cameras, sites, and participants. Three sites (Plant City, Medard Park, and Thonotosassa) were selected as typical i-Tree ECO data collection plots as discussed in Section 4. Figs. 4 and 5 show the sites' general layout and sample image taken

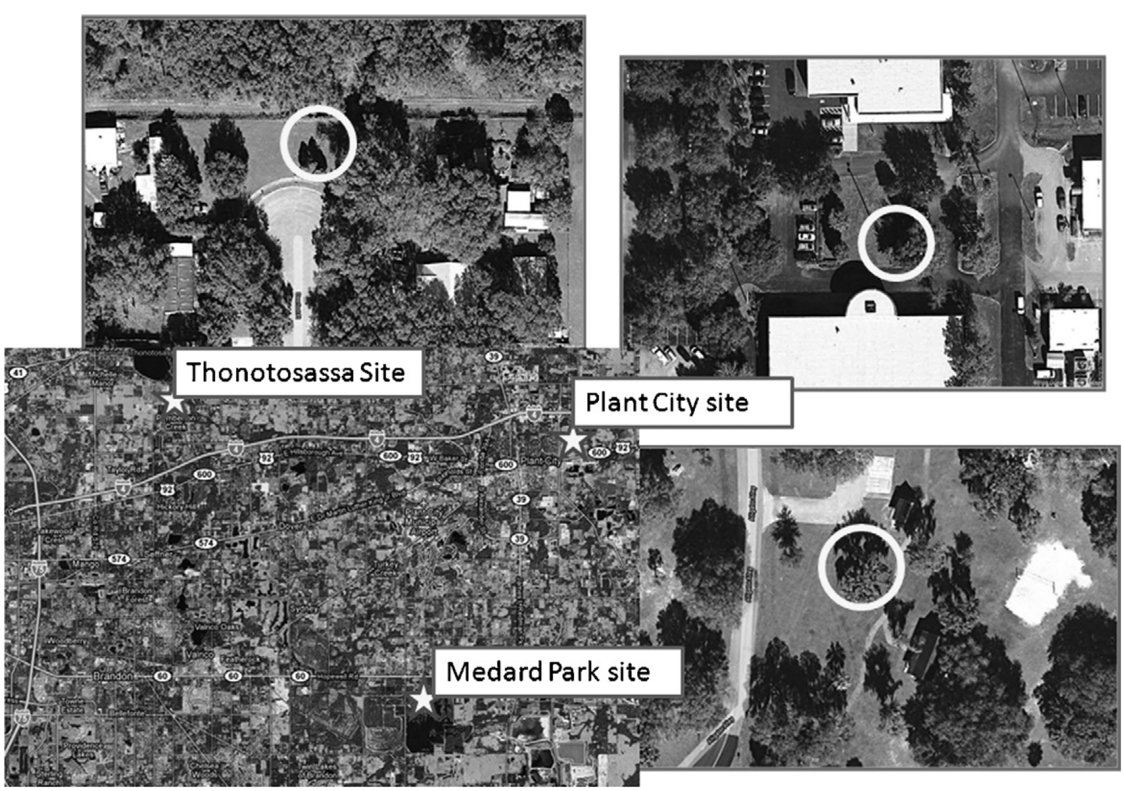

Fig. 4. Site locations and general layout.

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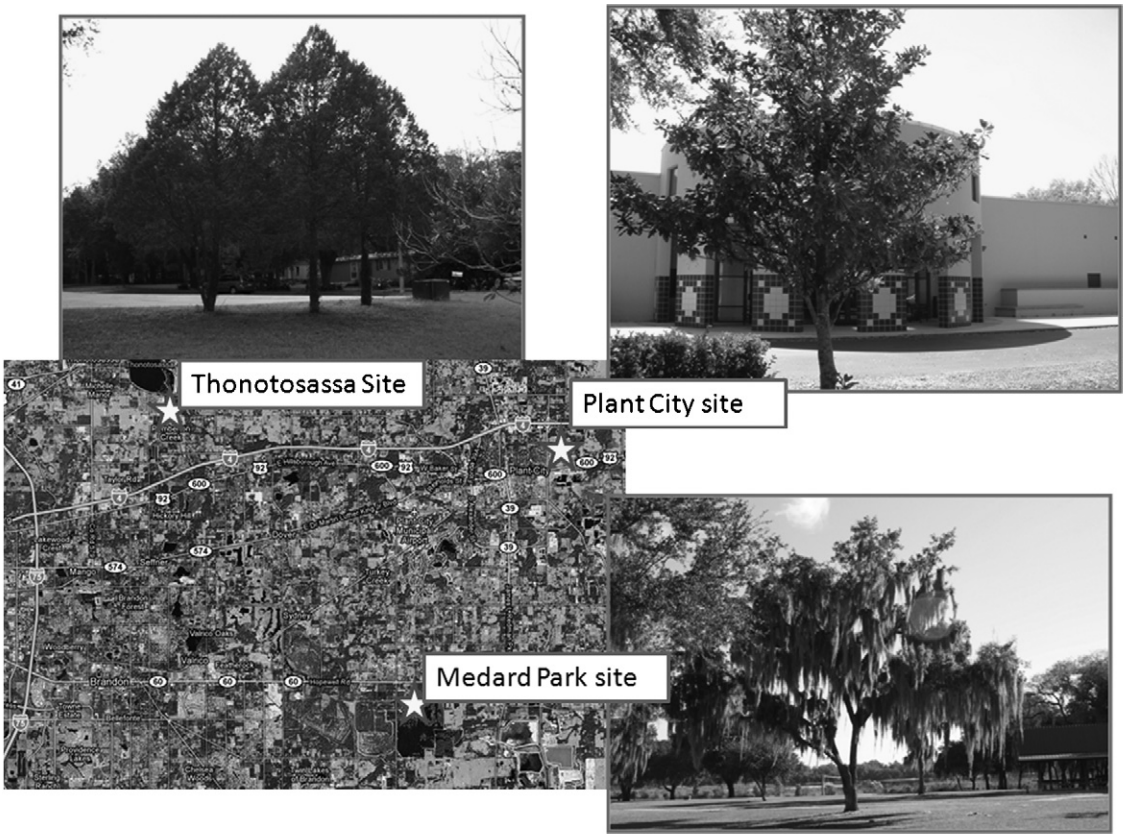

Fig. 5. Sample image taken at each site.

at each site, respectively. The first plot site (Plant City site) is located at the University of Florida's Plant City Center, which was used for our previous experiments. The other two sites are located inside one of the county parks (Medard Park site) and at a rural residential area (Thonotosassa site). Five different low-cost consumer-grade cameras were used by 4 different volunteers. A total of 8 photogrammetric solutions were solved and analyzed. Table 3 lists the camera type, the number of images, and the number of tie points used for the photogrammetric solutions performed at each site.

The participating volunteers were selected to have limited knowledge about photogrammetry. Our team involvement in the image acquisition process was restricted to providing written and verbal instructions regarding the imaging technique (e.g. capture overlapped converging images from different positions along circular arc) and the camera configuration (e.g. use manual camera setting). We think that with the availability of many outreach training programs, advanced multi-media technology, and web-based delivery methods, the type of instructions given to our volunteers could be achieved in a real world implementation.

Table 3
Photogrammetric solution information at each site.

Site	Camera	# Used images	# Tie points[a]
Plant City	HP E317	12	21
	Sony T10	7	25
Medard Park	Canon Xsi	5	18
	Kodak Z740	4	29
Thonotosassa (a)	Kodak Z712	4	25
	Kodak Z740	5	23
Thonotosassa (b)	Kodak Z712	4	19
	Kodak Z740	4	22

[a] The same tie points can be in multiple images.

One photogrammetric solution was performed for each camera-site combination (8 total solutions), except for the Thonotosassa site, which was split into two photogrammetric solutions due to the existence of multiple trees within the plot as shown in Table 3. Once the photogrammetric model was achieved, each model was scaled using a single distance measured in the field using a measuring tape. Several other distances were measured in the field using measuring tape to evaluate the accuracy of the photogrammetric solutions. Tables 4a–4c list the differences between the distances obtained through the photogrammetric solutions and the corresponding check distances for each photogrammetric solution.

4. i-Tree ECO data collection experiment

The i-Tree ECO data collection method has been used to assess urban forests throughout the United States (Eco User Manual, 2009). Sample plots are 0.04 ha circular plots that are randomly

Table 4a
Difference in distances obtained through scaled photogrammetric solutions and the corresponding distances measure by measuring tape for the Plant City site.

Ref line #	Plant City site				
	Ref. dist[a]	HP E317		Sony T10	
		ΔDist[a]	R.E.[b]	ΔDist[a]	R.E.[b]
1	3.32	0.07	2.1%	−0.22	−6.6%
2	12.34	0.01	0.1%	0.48	3.9%
3	7.99	0.45	5.7%	0.53	6.6%
4	3.95	0.20	5.0%	0.25	6.3%
5	2.44	0.03	1.2%	0.09	3.8%
6	1.77	0.07	3.8%	0.15	8.3%
Max		0.45		0.53	
Min		0.01		0.09	
RMSE		0.21		0.33	

Table 4b
Difference in distances obtained through scaled photogrammetric solutions and the corresponding distances measure by measuring tape for the Medard Park site.

Ref. line #	Medard Park site				
	Ref. dist[a]	Canon Xsi		Kodak Z740	
		ΔDist[a]	R.E.[b]	ΔDist[a]	R.E.[b]
1	1.33	−0.07	−5.5%	0.19	14.4%
2	20.92	−0.29	−1.4%	−0.31	−1.5%
3	12.82	0.59	4.6%	0.90	7.0%
4	3.63	−0.06	−1.6%	0.25	6.8%
5	6.11	0.06	1.0%	−0.34	−5.6%
6	2.94	0.01	0.4%	−0.19	−6.4%
7	5.99	0.28	4.6%	−0.32	−5.3%
8	2.36	0.17	7.2%	−0.24	−2.0%
9	12.42	−0.01	−0.1%	0.08	0.8%
10	10.60	−0.16	−1.5%	−0.37	−3.0%
11	12.32	0.31	2.5%	−0.56	−4.7%
12	11.92	0.43	3.6%	−0.24	−2.0%
Max		0.59		0.90	
Min		0.01		0.08	
RMSE		0.27		0.38	

allocated across a study area using a stratified, systematic or completely random sampling design. In a typical i-Tree ECO data collection process, trained crews visit the plots and collect quantitative and qualitative information at the plot and individual tree levels. Plot level data consists of information such as land use, percentage of tree and shrub cover and the percentage of space available to plant other trees within the plot. Individual tree data include specific information about each tree located inside the plot such as tree height, diameter at breast height (DBH), and crown width, etc. Typically, an i-Tree ECO crew uses different types of equipment. In the case of the City of Tampa's Urban Ecological Assessment (Andreu et al., 2008) conducted by our team, the i-Tree ECO crews were equipped with GPS receivers, clinometers, tree DBH tapes, tape measures and laser ace hypsometer to assist in speeding up distance measures. Information was collected on a paper data sheet and later entered into a spreadsheet program for inclusion in the tree inventory database. A single two person crew was able to collect data on an average of two plots per day (range 1–7 plots/day), depending on the distance between plots, accessibility to plots and density of sample vegetation.

We examined the use of our proposed community-based data collection photogrammetric solution to measure the three typical i-Tree ECO plots mentioned in Section 3.3 (Figs. 4 and 5). To examine the achieved accuracy, we compared the results of the photogrammetric solutions obtained by different cameras at each plot. The three-dimensional coordinates of the end points corresponding to the i-Tree ECO measurements (e.g. crown width, tree height and DBH measurement height) were determined by identifying each endpoint on at least two overlapping images and using the photogrammetric models to compute the coordinates. For example, the 3D coordinates of two points at the base and the top of the tree shown in Fig. 3 was determined to compute the tree height, which is one of the i-Tree ECO measurements taken by the field crew.

We also examined the high resolution aerial images accessed through the Google Earth^{TM} interface as another source of data that can be used in a community-based data collection context to complete the data set and provide verification to some of the information (e.g. crown width of individual trees). Aerial imagery has been a valuable source of information for forest information for decades. In this context, we introduced aerial imagery as a source of information that can complement the data acquired through the photogrammetric solution of ground imagery to achieve all data elements required for the i-Tree ECO analysis. Often local and state government agencies in the United States managing urban areas have plans for aerial image acquisition and update with intervals ranging from one to five years. In the Tampa Bay area, the South West Florida Water Management District leads a consortium of local and state agencies to collect 15–30 cm resolution aerial images covering the whole district annually since 2006. These images were made available online through commercial mapping services or through the agencies websites. Tables 5a–7b summarize the i-Tree ECO data collected for the test plots using photogrammetric techniques, aerial images and field measurements. Each table was split into two parts: part a, which shows the i-Tree ECO data elements for individual trees on the site; and part b, which presents the general information on the plot level. It should be note here that only the information for two trees (out of 4 existing trees) in the Thonotosassa site was included as examples of the site content.

5. Analysis and discussion

5.1. Web-based application development and implementation

The collection of urban forest information through a web application was built around the Google Maps^{TM} interface. Plot and tree locations are identified and input by clicking on the Google Maps^{TM} interface. The interface is also used for displaying the results of a user's query. Current common programming tools such as Java scripting and .net application development framework were used.

Table 4c
Difference in distances obtained through scaled photogrammetric solutions and the corresponding distances measure by measuring tape for the Thonotosassa site.

Ref. line #	Thonotosassa a					Thonotosassa b				
	Ref. dist[a]	Kodak Z712		Kodak Z740		Ref. dist[a]	Kodak Z712		Kodak Z740	
		ΔDist[a]	R.E.[b]	ΔDist[a]	R.E.[b]		ΔDist[a]	R.E.[b]	ΔDist[a]	R.E.[b]
1	1.13	0.34	29.7%	0.24	21.2%	2.94	−0.48	−16.3%	−0.41	−13.9%
2	14.29	0.04	0.3%	0.00	0.0%	2.59	−0.34	−13.0%	−0.27	−10.2%
3	14.39	0.02	0.2%	0.01	0.1%	2.96	0.14	4.9%	0.18	6.0%
4	12.20	0.72	5.9%	−0.24	−2.0%	1.40	−0.08	−5.9%	0.01	0.9%
5	13.33	−0.16	−1.2%	0.18	1.4%	4.28	−0.04	−0.8%	0.03	0.6%
6	14.30	0.01	0.1%	0.04	0.3%	7.20	−0.63	−8.7%	−0.49	−6.8%
7	14.32	0.06	0.4%	0.05	0.3%	2.65	0.09	3.3%	0.11	4.1%
8	14.35	0.07	0.5%	0.01	0.1%	2.65	0.00	−0.1%	0.05	1.9%
9	12.38	1.04	8.4%	0.12	1.0%	6.68	−0.39	−5.8%	−0.29	−4.4%
Max		1.04		0.24			0.63		0.49	
Min		0.01		0.00			0.00		0.01	
RMSE		0.44		0.14			0.32		0.26	

[a] All distances are in meters.
[b] Relative error is the (error/Ref. dist)%.

Table 5a
Summary of plant inventory using different data sources at the Plant City plot site.

Category	i-Tree ECO data element	Field measurements	Google aerial	Photogrammetry	
				Sony	HP
Tree inventory	ID #	1	1		
	Species	*Magnolia grandiflora*	◊		
	# of DBH's[b]	1		1	1
	DBH Measurement Ht	1.10 m		1.04 m	1.08 m
	DBH[c]	0.18 m		0.2 m	0.18 m
	Tree height	7.32 m		◊[a]	◊[a]
	Crown-base height[d]	1.52 m		1.45 m	1.50 m
	Crown width	5.09 m		5.28 m	5.42 m
	% Missing[e]	5		0[a]	0
	% Dieback	0		0	0
	Crown light exposure	4	4	4	4
	No. buildings within 60 ft.	1	1	1	1
	Building distance	17.5 m	18.18 m	18.58 m	17.49 m
	Building direction	South	South	South	South
	Street tree? (y/n)	n	n	n	n

[a] ◊: unable to determine.
[b] # of DBH's: trees may have more than one trunk.
[c] DBH: diameter at breast height.
[d] Crown-base height: the distance from the ground to the bottom of the tree crown.
[e] % missing tree canopy.

Table 5b
Summary of general information collected on the plot with the use of different data sources at the Plant City site.

Category	i-Tree ECO data element	Field measurements	Ground images/google aerial images
Plot information[a]	Land use	Educational	
	Land use %	100	100
	Shrub %	10	10
	Tree %	30	25
Ground cover information[b]	Building %	0	0
	Cement %	0	0
	Tar %	20	15
	Other impervious %	0	0
	Soil %	0	5
	Pervious rock %	0	0
	Duff/mulch %	15	10
	Herb/ivy %	5	0
	Grass %	60	70
	Unmaintained grass %	0	0
	Water %	0	0

[a] Plot information concerns the entire plot.
[b] Ground cover information concerns the entire plots ground cover.

Table 6a
Summary of plant inventory using different data sources at the Medard Park plot site.

Category	i-Tree ECO data element	Field measurements	Google aerial	Photogrammetry	
				Canon Xci	Kodak Z740
Tree inventory	ID #	1	1	1	1
	Species	*Quercus virginiana*	◊	*Q. vir*	*Q. vir*
	# of DBH's[b]	1	◊[a]	1	1
	DBH measurement Ht	1.37 m	◊[a]	1.40	1.33
	DBH[c]	0.64 m	◊[a]	0.56	0.52
	Tree height	12.46	◊[a]	12.14 m	12.02 m
	Crown-base height[d]	1.875 m	◊[a]	1.87 m	1.83 m
	Crown width	15.7 m	14.03 m	15.00 m	15.70 m
	% Missing[e]	0	◊	0	0
	% Dieback	0	◊[a]	0	0
	Crown light exposure	5	5	5	5
	No. buildings within 60 ft.	None	None	None	none
	Building distance	0	0	0	0
	Building direction	0	0	0	0
	Street tree? (y/n)	n	n	n	n

[a] ◊: unable to determine.
[b] # of DBH's: trees may have more than one trunk.
[c] DBH: diameter at breast height.
[d] Crown-base height: the distance from the ground to the bottom of the tree crown.
[e] % missing tree canopy.

Table 6b
Summary of general information collected on the plot with the use of different data sources at the Medard Park site.

Category	i-Tree ECO data element	Field measurements	Google/aerial images
Plot Information[a]	Land use	Recreational	Recreational
	Land use %	100	100
	Shrub %	0	0
	Tree %	75	80
Ground cover information[b]	Building %	0	0
	Cement %	8	5
	Tar %	0	0
	Other impervious %	0	0
	Soil %	0	0
	Pervious rock %	0	0
	Duff/mulch %	0	0
	Herb/ivy %	0	0
	Grass %	92	95
	Unmaintained grass %	0	0
	Water %	0	0

[a] Plot information concerns the entire plot.
[b] Ground cover information concerns the entire plots ground cover.

Most of the tools and software utilized in the application development were free of charge. Our main cost was in the labor associated with the application's development. The UFIA application facilitates extensive search capabilities based on information stored on the database such as plot location and plant type. Redundancy in the spatial domain can be used to extract additional information from the data set that is not explicitly part of the application database schema. The potential findings of undesirable vegetation communities or those that may be scarcer may be used to inform decision makers and support the initiation of certain management and education programs (Thornhill et al., 2009).

One of the basic issues associated with any community-driven data collection procedure is the level of trust we can put into this data. There is less control over this type of data in terms of the uniformity of both the collection process and the data itself. However, redundancy can provide a powerful and statistically valid method of verifying data. This can be achieved by crosschecking spatially co-occurring data entered by different community members, send-

Table 7a
Summary of plant inventory using different data sources at the Thonotosassa plot site.

Category	i-Tree ECO data element	Field measurements	Google aerial images	Photogrammetry	
				Kodak Z712	Kodak Z740
Tree 1					
Tree inventory	ID #	1	1	1	1
	Species	*Magnolia grandiflora*	◊	*M. gran*	*M. gran*
	# of DBH's[b]	3	◊[a]	3	3
	DBH measurement Ht	1.37 m	◊[a]	◊[a]	◊[a]
	DBH[c]	0.122 m/0.079 m/0.051 m	◊[a]	◊[a]	◊[a]
	Tree height	7.1 m	◊[a]	6.24 m	6.43 m
	Crown-base height[d]	1.37 m	◊[a]	1.59 m	1.413 m
	Crown width	5.17 m	3.52 m	6.64 m	6.32 m
	% Missing[e]	50	◊	40	40
	% Dieback	40	◊[a]	40	40
	Crown light exposure	5	5	5	5
	No. buildings within 60 ft.	None	None	None	None
	Building distance	0	0	0	0
	Building direction	0	0	0	0
	Street tree? (y/n)	n	n	n	n
Tree 2					
Tree inventory	ID #	2	2	2	2
	Species	*Juniperus salisicola*	◊	*J. salis*	*J. salis*
	# of DBH's[b]	3	◊[a]	3	3
	DBH measurement Ht	1.37 m	◊[a]	◊[a]	◊[a]
	DBH[c]	0.135 m/0.053 m/0.081 m	◊[a]	◊[a]	◊[a]
	Tree height	6.38 m	◊[a]	5.61 m	5.8 m
	Crown-base height[d]	1.52 m	◊[a]	1.47 m	1.37 m
	Crown width	4.32 m	◊	4.25 m	4.60 m
	% Missing[e]	5	5	5	5
	% Dieback	0	◊[a]	0	0
	Crown light exposure	3	3	3	3
	No. buildings within 60 ft.	None	None	None	None
	Building distance	0	0	0	0
	Building direction	0	0	0	0
	Street tree? (y/n)	n	n	n	n

[a] ◊: unable to determine.
[b] # of DBH's: trees may have more than one trunk.
[c] DBH: diameter at breast height.
[d] Crown-base height: the distance from the ground to the bottom of the tree crown.
[e] % missing tree canopy.

Table 7b
Summary of general information collected on the plot with the use of different data sources at the Thonotosassa site.

Category	i-Tree ECO data element	Field measurements	Google/aerial images
Plot information[a]	Land use	Residential	Residential/natural
	Land use %	100	75/25
	Shrub %	0	3
	Tree %	20	30
Ground cover information[b]	Building %	0	0
	Cement %	5	9
	Tar %	0	0
	Other impervious %	0	1
	Soil %	0	15
	Pervious rock %	0	0
	Duff/mulch %	0	2
	Herb/ivy %	10	2
	Grass %	85	70
	Unmaintained grass %	0	2
	Water %	0	0

[a] Plot information concerns the entire plot.
[b] Ground cover information concerns the entire plots ground cover.

ing verification field crews or by utilizing alternative sources of data such as ground, airborne or satellite images. Our method of incorporating ground images provides a whole new category of data that can be integrated into the data quality control and assurance procedures. Not only can metric information be verified using alternative data sources, but qualitative data such as tree-shrub type and land use can also be recovered and verified from the images. We expect that intelligent procedures that analyze data spatially and temporally can be built on an accumulated database to assist in the data quality control efforts.

Although, the UFIA application is still in a prototype testing mode, we believe that releasing the application for use to targeted audience should be accompanied with extensive training material. Apart from the necessary training on plant identification, information on best practices in image acquisition is necessary for a successful photogrammetric solution. From our outreach activities we know it is viable to design an experiment where members of environment-related groups (e.g. Master Gardeners of Florida), who are required to do certain number of hours of voluntarily work, can use our randomly allocated circular urban forest plots for measurements. One site can be visited by multiple volunteers and a single volunteer can visit multiple sites.

5.2. Photogrammetric solution accuracy analysis

Photogrammetric solutions are normally preceded with a planning phase (Luhmann et al., 2007). Before actual image acquisition, special targets are carefully established and observed. For applications that require high accuracy, calibrated metric cameras are used. In our proposed community-based data acquisition approach, many of these precautions simply cannot be satisfied. In our solution, we utilized un-calibrated non-metric consumer-grade cameras with asphalt patches, leaf edges and tree marks as tie and control points. We observed some of the selected points by a total station in either a reflector-less or a reflector mode to get coordinates for the used control and check points.

Table 1 listed the differences between the coordinates of the check points computed from the photogrammetric solution and the observed ones. As mentioned earlier, one of the check points showed an error of more than 20 cm. When analyzing the standard deviation of the photogrammetric solution point coordinates, which is a standard output of the bundle adjustment process, we found that this point had the worst precision (highest standard deviation) among all computed coordinates. Table 1 showed that the RMSE for the check points in the x, y and z directions were 1.3, 4.6 and 3.4 cm, respectively, with an average total error of 5.5 cm. The differences between the computed and surveyed check point coordinates in the x, y and z directions were generally below 6 cm. This is a promising result for researchers and professionals working in the urban forest and in many natural resource management fields, knowing that this result was obtained using high-end consumer-grade camera with multiple images in an urban environment and using surveyed control points.

Our second test results (Table 2) showed a RMSE value of less than 16 cm for 10 check distances when a scaled photogrammetric solution was used. These errors represented the differences between 10 distances computed from the scaled photogrammetric model and the photogrammetric model solved using surveyed control points. We performed this test using three different scaling baselines with distances representing short (2.69 m), medium (17.50 m) and relatively long (24.42 m) baselines. Although the resulting RMSE in all tested cases were close in value, we believe that a photogrammetric solution that incorporates more than one distance for constraints in the bundle adjustment process should give higher accuracy. Measuring more than one base line is a fairly easy process and can be conducted by the average citizen. However, few low-cost photogrammetric software programs accommodate linear constraints in their solutions. As an applied short term fix, the photogrammetric model can be scaled multiple times with different baseline distances. The coordinates extracted from each scaled model can be averaged to extract more reliable metric information.

Tables 4a–4c showed the differences between several check distances measured by a measuring tape and their corresponding distances extracted through the photogrammetric solutions obtained using lower grade cameras in different sites. Unlike the high-end consumer-grade Nikon camera used for the results demonstrated in Tables 1 and 2, the cameras used for the data presented in Tables 4a–4c can be less stable and suffer from higher lens distortion effect. The RMSE of the differences presented in Tables 4a–4c were generally less than 0.45 m. Although the maximum error obtained in some of the solutions was around 1 m, the relative error for these distances was generally low, which supports the photogrammetric solution's appropriateness for longer distance measurements.

5.3. i-Tree ECO inventory analysis

Two different types of i-Tree ECO inventory data were examined. The first type of data was site or plot related, while the other type was related to individual trees. Data was collected using field measurements, online Google^{TM} aerial images and/or photogrammetric measurements. The photogrammetric solution of the i-Tree ECO

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inventory test was performed by 8 different image sets taken by volunteers using different consumer-grade camera types at different sites (Table 3).

The results demonstrated in Tables 5a–7b indicate that nearly all i-Tree ECO data elements can be retrieved using the online Google™ aerial images and the measurements obtained from the photogrammetric solutions. Although we used online aerial images in our study, we recognize that offline images can also be used. Annually, updated high resolution aerial images for the west central Florida region are available free of charge for download from some governmental agencies and GIS data repository websites. Combining aerial image observations with detailed photogrammetric measurements means that virtually all quantitative field observations by i-Tree ECO trained crews can be eliminated and substituted by information and ground images gathered and sent by community participants and/or lab measurements performed by the researchers on uncomplicated i-Tree ECO plots.

Measurements extracted from the photogrammetric solutions covered most of the individual tree data such as crown diameter or height at DBH (Tables 5a, 6a and 7a). General site information such as land use or tree cover percentage was difficult to obtain directly from ground images alone. This type of data was more readily extractable through observations and measurements from the aerial imagery in addition to visual interpretation of the ground images (Tables 5b, 6b and 7b). We believe that the difficulties in obtaining accurate ground cover information from the photogrammetric solution could be mitigated by taking additional plot images and adopting certain image capturing practices. For example, the images need to be taken while the plot boundary is physically marked so that it is visible in the images. A series of images may need to be taken from outside the boundary of the plot towards the center and span as much as possible of the whole plot circumference. This practice could allow plot and ground cover percentages to be accurately determined for the entire plot using the ground images in place of (or as redundant to) the aerial images.

In some cases, redundant measurements were obtained using the ground and aerial image datasets. For instance, the distance between a tree and closest building can be approximately identified and measured from the photogrammetric solution in addition to direct measurement from the aerial image. The visual inspection of the ground images was also effective in estimating some of the i-Tree ECO data elements. For example, the percentage of missing crown can be estimated by visual interpretation of some of the captured ground images. On the other hand, most qualitative information such as tree species is hard to obtain from the aerial or ground images. Newly developed outreach training and education programs such as The Community Forest Stewards has been developed in 2009 for community members and Forest Stewards to be trained in the fundamentals of tree identification. This type of programs can be used for direct training of community members. They also can be modified and delivered as online training material for a broader outreach.

Tables 5a and 5b showed the differences between several i-Tree ECO distances that were measured by the field crew and their corresponding distances extracted through the photogrammetric solutions. Most differences can be accepted and may be better than what we expected given the measurement technique used by actual field crews (Eco User Manual, 2009) and the difficulties in defining clear end points of measured distances in nature and on the images. Some of the distances were hard to measure through the photogrammetric solution due to lack of image coverage (e.g. the images taken for the Plant City plot did not cover the top of the Magnolia tree), or lack of definite points that can be marked on overlapped images (e.g. points to get diameter of the tree trunks at the Thonotosassa site). As discussed earlier, higher confidence should be put on longer distances due to expected low relative error. Fortunately, small distances can easily be measured by a trained community member and provided directly through the web interface.

Our tests showed that the obtained accuracy was improved by incorporating images taken by the camera rotated approximately 90° and −90°. Including these images into the photogrammetric solution enhances the self-calibration bundle adjustment and produces better camera calibration parameters [e.g. (Brown, 1989; Hartley, 1997)]. If the rotated images are not included, parts of the images (e.g. tree top areas) will not have enough conjugate points to obtain appropriate camera calibration parameters. Although the incorporation of more rotated images will add to the instructions given to the community members and to the solution processing time, we think that the improvement in the overall model accuracy would justify these complications.

The results discussed in this study demonstrate the feasibility of using photogrammetry to supplement or replace field measurements in urban forest inventories and hence, its integration into community-based data collection applications. Nevertheless, the results revealed some of the shortcomings of the utilization of amateur photogrammetric solutions with many of the used tie points being natural objects (e.g. leaf edges and tree marks). Issues such as the low relative accuracy and the inability to sharply identify conjugate points in the overlapped ground images would require an increase in community participation so that a more robust sample of redundant measurements would be provided. A densely vegetated plot may affect the efficiency of the photogrammetric solution and will definitely affect our capabilities to identify objects from the aerial images.

We recognize that our proposed method cannot completely replace traditional forest inventory techniques in areas where there are no community participants. However, it could be used to make more efficient use of crews by utilizing them in more complex plots that involve a large number of trees or closed tree canopies. This reality will require exploring changes in the adopted sampling strategy and inventory methods if it is to be applicable to these areas as well. However, we believe that a wide spread deployment of volunteers in a community-based data collection program could be used as an outreach and extension education effort that could result in a proactive process that urban forest programs can use to supplement or modify data collection technique to better meet the needs of the community.

6. Conclusion

We established a methodology for community-based data collection through a web application built around the Google Maps™ interface. The Google Maps™ interface was used for spatially referenced data display and input. The application was designed to collect urban forest inventory information by interested community participants. The application also allowed for uploading images taken using consumer-grade cameras for quantitative and qualitative information extraction. Two experiments were designed to test the accuracy of the photogrammetric solution using images taken by high-end consumer-grade digital camera and surveyed control points. A bundle adjustment photogrammetric solution was carried out by solving for the images relative orientation parameters followed by a single baseline model scaling. The average total error in the check points was 5.5 cm for the photogrammetric solution that utilized surveyed control points. The results of the solution obtained using a relative orientation process, followed by a model scaling process was compared with the control-assisted photogrammetric model results. The RMSE of the differences in 10 check distances was in the mid-teen centimeters.

The feasibility and quality of the metric data extracted from images captured by five different types of low-cost consumer-grade cameras using photogrammetric solutions were investigated. The results of the photogrammetric solutions were assessed by comparing distances extracted through the model solution with check distances measured in the field. The RMSE of the differences was less than 0.45 m. An i-Tree ECO plot was sampled using field crew and from photogrammetric solutions of images taken by the research team and a volunteer. Plot level land cover information was collected using the field crew observations and available aerial images. The research proved the potential for using community-based data collection, through web applications powered by web-based mapping services, to supplement urban forest inventory efforts. Many of the shortcomings of the suggested technique were discussed. The need to provide training and educational programs for participated community members was highlighted as an essential element to successfully implement the suggested community-based data collection techniques.

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