

# iCam<sup>1</sup>: Precise at-a-distance Interaction in the Physical Environment

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**Abstract.** Precise indoor localization is quickly becoming a reality, but application demonstrations to date have been limited to use of only a single piece of location information attached to an individual sensing device. The localized device is often held by an individual, allowing applications, often unreliably, to make high-level predictions of user intent based solely on that single piece of location information. In this paper, we demonstrate how effective integration of sensing and laser-assisted interaction results in a handheld device, the iCam, which simultaneously calculates its own location as well as the location of another object in the environment. We describe how iCam is built and demonstrate how location-aware at-a-distance interaction simplifies certain location-aware activities.

## 1 Introduction and Motivation

We have seen great progress in our research community towards the goal of practical, precise indoor localization. A variety of techniques, including those that introduce new infrastructure (e.g. ultrasound [20, 2], camera tracking [28], ultra-wideband [24]) and those that leverage existing infrastructure (e.g. 802.11 [3, 12], GSM [18], Bluetooth [14]) show that we are not far off from having everyday devices that know where they are in the physical world.

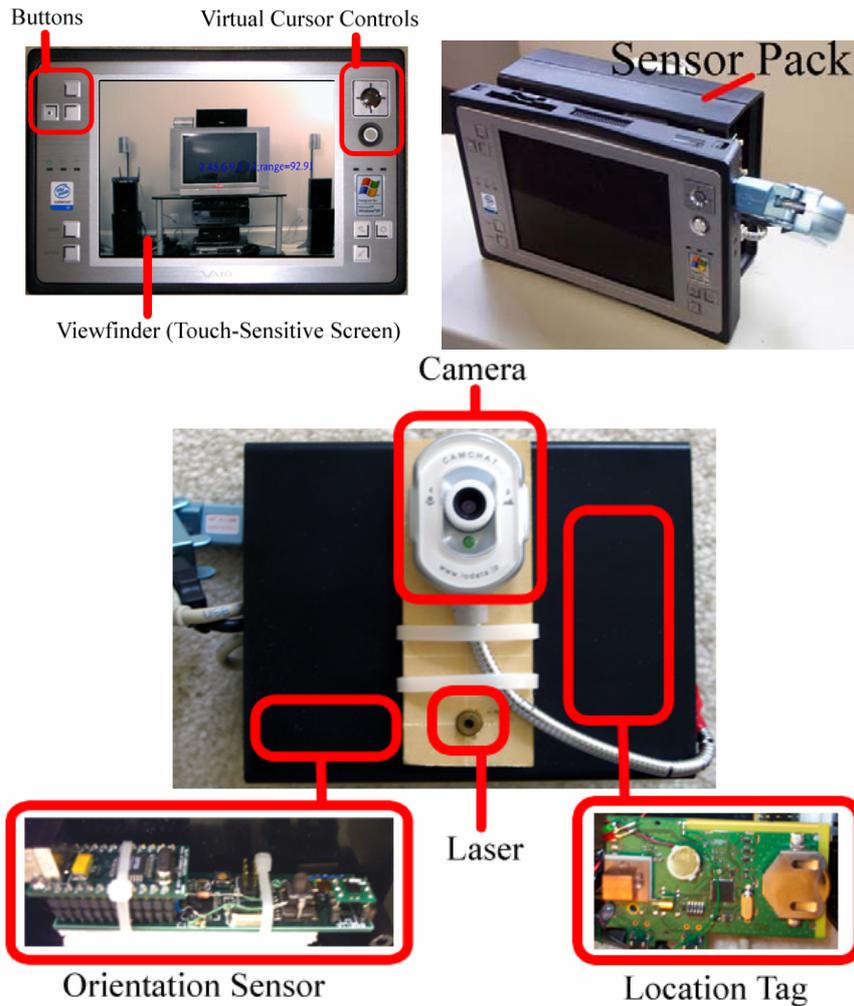
Location-aware applications are limited, however, when using only knowledge of a single object's location. This location information is usually that of the device itself, and applications assume that the device is in the possession of an individual. In that case, device location relates to the owner, and services provided are dependent on the owner's assumed location. This technique is unsatisfactory for applications, such as the canonical mobile tour guide, in which focus of attention, not just location, may be the desired trigger for delivering information (*e.g.*, for what object is the tourist wanting further information) [1, 8].

One augmented reality solution is to gain precise location and orientation information of the individual and project information about the world in the field of view of that individual. However, it can be difficult to place content in the environment, that is, to create the link between physical location and virtual information. Another solution is to

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<sup>1</sup> Title and device name has been modified for anonymity

tag the environment with glyphs and recognize those tags, usually through some form of computer vision. Tagging is not always feasible or aesthetically desirable, though this solution does allow for objects to be moved in the environment and does not require precise localization.



**Figure 1:** The iCam handheld. The back of the device (shown on the bottom) houses the laser pointer and the camera in addition to the collection of sensors inside the housing.

In this paper, we provide another alternative: augmenting a precisely located device with a laser-based range finder so that it can also accurately determine the location of an object at-a-distance. We describe the iCam handheld device as a demonstration of this concept (shown in Figure 1). iCam integrates a commercially available indoor ultra-wideband positioning system [24] with a magnetic compass, an accelerometer, a camera,

and a laser pointer. This portable handheld device tracks its own location and orientation to within 7 cm and 1.5 degrees of rotation. By using the laser pointer, a user can point to any object or surface in the physical environment, and iCam calculates that object's absolute 3D location to 10 cm accuracy from a distance of up to 5 meters. With this capability, we demonstrate how one can use iCam to place information at any arbitrary location in the environment and how it can greatly simplify the authoring of location-triggered content. The same iCam handheld features a camera which allows users to view any digital content through an augmented viewfinder.

The important contribution of this paper is a demonstration of how simultaneous knowledge of two pieces of location information simplifies aspects of the location-aware experience, both from the user and developer perspectives. Among those tasks that are made easier are overall system calibration, creation of a map of the physical environment, and attaching virtual information to physical locations.

In this paper, we first describe the related work and then illustrate the user experience this system enables. Next, we present a location-based tour guide application that leverages iCam's unique capabilities, describe the detailed implementation of iCam, and then finish up with future work and conclusions.

## 2 Related Work

Although comprehensive surveys of location technology and location-aware applications are not practical for this paper, we will highlight some notable examples. Researchers have extensively studied indoor location technologies. Hightower provides an overview of the various location technologies and techniques [9]. The two basic approaches are to build the entire sensing infrastructure from the ground up (*e.g.*, ActiveBadge[26], Cricket[20], and Active Bat[2]) or to leverage existing infrastructure that can yield localization, either through triangulation or fingerprinting (*e.g.*, 802.11 work such as RADAR[3] and Place Lab[12], GSM [18], and Bluetooth [14]). Applications that leverage some of these location technologies started with the original location research at Olivetti and Xerox PARC, where researchers used office tasks as motivation to create experiences such as Audio Aura, auto call forwarding, and desktop migration [16, 26]. Location information has also been used to trigger events and reminders in applications like Forget-me-not and CybreMinder [6, 11]. Later, researchers utilized location-awareness in tourist applications to help people navigate and explore unfamiliar spaces, such as with CyberGuide [1] and GUIDE [4].

Location has been used both implicitly and explicitly to attempt to describe and interact with the physical world. Researchers have explored selection of physical objects in an environment for various augmented reality tasks (*e.g.*, NaviCam [23]), which includes ways to tag the physical world using printed barcodes, 2-dimensional glyphs [22, 23], RFID, and active beacons [25] to connect the physical and electronic worlds. The applications created with this technique demonstrate the potential of leveraging knowledge of the world beyond just the location of the device or individual. However, the current solutions that use static labels (such as barcodes or 2-dimensional glyphs) are limited in distance due to the camera resolution and perception techniques used to deci-

pher the glyphs. Static labels are also not practical to deploy in highly interactive spaces because of the difficulty inherent to placing labels on every object.

Previous research projects have also explored laser pointer interaction, both for interaction at-a-distance with large displays [5, 10, 15, 17] and for the selection tasks of physically tagged objects [19, 21]. A popular laser pointer interaction scheme is to use a camera focused on a region of a wall or object in which a laser spot may appear. Simple computer vision techniques locate the red laser dot and follow it around the interaction region. Such a scheme is appealing for meetings or presentations, during which one can interact with a display from a distance by simply pointing at it with an ordinary laser pointer. Two-way laser pointing techniques have been proposed using active tags placed in the environment, but these are subject to the same scalability limitations as static tags mentioned previously.

The XWand system demonstrates how individuals can use laser pointing techniques with a collection of other sensors to support selection of and interaction with devices through a special-purpose device [28]. Although this camera-based tracking solution provides very flexible ways to point and select objects within the environment, it requires significant overhead in terms of camera infrastructure. An extension of XWand, called the World Cursor, removes the vision requirement by using the XWand to steer a remotely controlled laser pointer around a room [27]. The remotely controlled laser pointer has a model of where it is pointing in 3D-space and has sufficient geometric information to know where its red laser dot is pointing. The drawback of this is that it is limited to objects that are within the line-of-sight of the steerable laser. For example, it would be difficult to interact with the sides of an object placed against the wall. iCam's mobility addresses some of these problems.

The drawback of these approaches is the time-consuming setup and calibrations and the fact that they do not provide an easy way to add or edit digital content. Most systems assume a model of the space and attributes of the objects that are preprogrammed. Although iCam requires a 3D model of the space, we provide a very quick and easy means to define that model.

### 3 Demonstrating the iCam Experience

#### 3.1 The iCam Experience

iCam supports two basic modes of interaction. The first is a simple *seeking* or gathering of information from the physical and virtual space. The second is *defining* the geometry of the physical space and the digital content that may appear within it. This includes the calibration of the infrastructure, the mapping and defining of the physical space, and the authoring and attaching of virtual content.

A laser pointer mounted on the handheld produces a bright red dot that iCam uses to target objects or places of interest. For example, a user can use the visible laser dot to point at a light switch or trace the outline of a door by moving the dot around the door-

frame (see Figure 2). Additionally, users can interact with the space between the handheld device and the position where the dot lands by moving a virtual cursor on the viewfinder up and down the beam produced by the laser pointer. This movement of the cursor allows interaction within the free space where there may not be physical artifacts for the dot to actually land on. If the user is interested in scanning the space for information, iCam can be used similarly to a video camera (such as when recording a video of a scene) to find the relevant information in the area.

### 3.1.1 Seeking Information

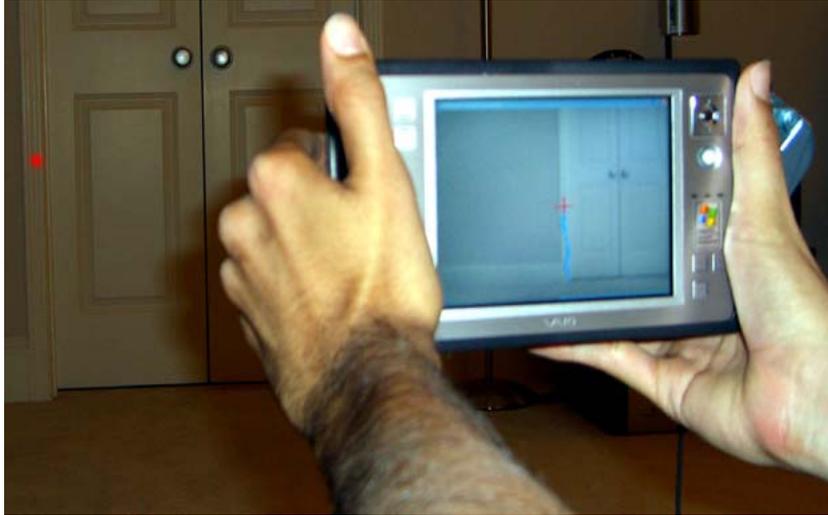
For seeking information, iCam is used much like a video camera in that the user can scan the space and see augmentations of digital content, such as textual information or pictures, over the live view of the physical space (see Figure 3d). A user can also interact with the physical space, such as actuating a light switch by pointing at it and pressing a button on the handheld. More complicated widgets may also be available in the space. In the light switch example, the physical switch could be augmented with additional control options (*e.g.*, timing, mood lighting, or dimming capabilities) that appear over the physical switch when the user points at it. The user can then use the virtual cursor in the augmented view to interact with the virtual switch.

iCam also supports zooming to obtain different levels of detail in the scene. If the user is interested in viewing the available virtual content for a space, he can use the zoom out feature to view a large amount of available content quickly and to reduce the amount of movement for scanning the space. Likewise, zooming into a scene can reveal more detailed information. Zooming also enables long distance interaction. If the laser dot is not easily viewable, the user can zoom in and use the virtual cursor to do fine-grained movements from a distance.

### 3.1.2 Defining the Physical Space and Placing Content

iCam provides an easy method for defining the physical layout of a space (see Figure 2). Users can trace parts of the physical space, similar to outlining with a pen, by using the laser dot as the visual feedback. The viewfinder provides feedback of the trail or “ink” left behind with the trace, which allows users to view exactly what was marked. The accuracy of the system allows users to provide detailed selections of the areas of interest. This selection method allows a person to quickly produce a geometric model, such as by tracing the outlines of the walls, doors, and windows of a room.

We provide a very simple content addition mechanism called *beaming*. Beaming involves the attachment of authored content, such as a note, anywhere in the physical space. Users can create content using the iCam interface or import it from another computer system. After producing the content, the user can either beam it to where the laser dot lies or place the authored content in free space by moving the virtual cursor displayed in the viewfinder along the laser beam.



**Figure 2:** Example of a user tracing the door frame to create a map of the space. Notice the virtual ink left behind through the viewfinder for visual feedback.

### 3.2 Tour Guide Application

To demonstrate the use and capabilities of the iCam system, we revisit the canonical tour guide example. Although this is a popular application in many location-aware systems, an often unaddressed but important task for these applications is creating the digital representation of the physical space. Especially for precise indoor solutions, some level of a geometric model of the space is a necessary component. Thus, we focus on a tour guide application that provides an easy way to create the tour itself.

Our system provides a very easy way to define the map of the physical space by using a special “learning” mode. A user can walk around the space and add annotations to physical objects. The tour creator would create the content on the iCam and beam it to the appropriate physical artifact by pointing at it. Arrows can also be placed in the environment to suggest where to go next from each exhibit. In this case, the tour creator would find an appropriate location and draw a line where an arrow should appear, where the endpoint of the line indicates the direction of the arrow. The creator can also make free hand annotations by using iCam as a pen to mark and produce callouts. Additionally, a user can take a snapshot of the current view, use a stylus to draw directly on the display, and then place the annotation back into the environment. This is desirable since it may be difficult to control the laser for certain strokes, especially from very far distances.

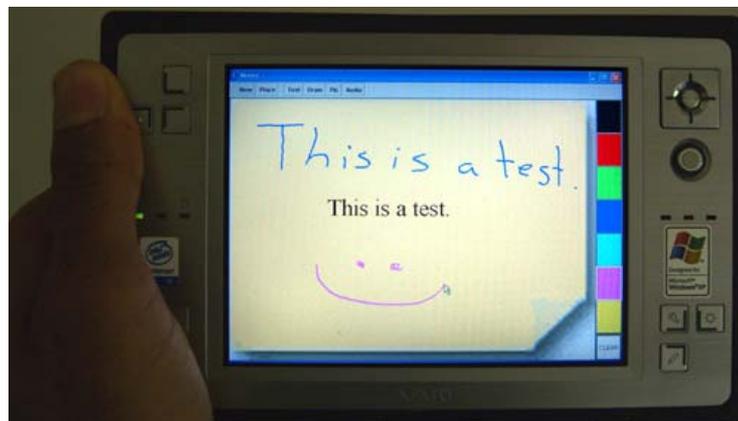
Figure 3 (a-d) shows a simple note or content creation interface. The interface consists of a blank note where the user can place any combination of pictures, text, free-hand writing, or short audio clips. The user selects the type of content he wants to add from the toolbar and places it on the note. He can insert pictures by looking through a list of image files on the device, enter text by using the handheld's virtual keyboard, add

free-hand writing by directly writing on the screen with a finger or stylus, or add an audio note by speaking into the onboard microphone. If the user chooses, he may also import pre-authored content from a remote computer and attach it to the notes created with iCam.

During a tour, the iCam displays the annotations and virtual content through the viewfinder while it is pointed toward the relevant parts of the physical space. Every user will see the same content from every vantage point, similar to how it would look if it were a physical artifact in the space. A user can view all the available annotations in an area by scanning the space with the viewfinder and using the zooming capabilities.



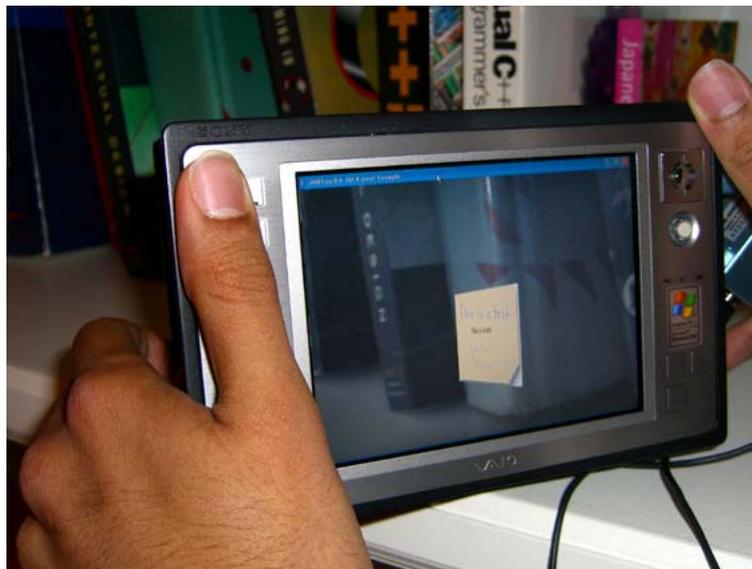
(a) The user scans the physical environment to find a place to add new content.



(b) He then authors the content using the iCam's notes interface.



(c) The user beams the created note to the desired location on the bookshelf.



(d) The user views the same note from a different vantage point.

**Figure 3 (a-d):** An example of using iCam to create a note, place it in the environment, and then view it.

#### 4 iCam Implementation Details

iCam is a handheld device (show in Figure 1) that can accurately locate its position and determine its absolute orientation when it is indoors. It can also determine the 3D

position of any object to which points with its onboard laser pointer. iCam is built using a Sony Vaio Type-U handheld instrumented with a variety of onboard sensors. The device can localize its position in 3D space to within 7 cm of accuracy, determine its orientation (azimuth, tilt, and roll) within 1.5 degrees, and determine the 3D location of other objects and surfaces within 10 cm in all directions.<sup>2</sup> It accomplishes this by integrating a modified version of a commercially available, ultra-wideband location system (from Ubisense [24]), a 3-axis magnetic compass, a 2-axis accelerometer, and a laser pointer tracked by the handheld's camera. The net location update rate is 15 Hz, which is enough for most interactive applications.

#### 4.1 3D Position

The handheld determines its location using the Ubisense ultra-wideband location system installed in the environment. We chose to use the Ubisense system because of its commercial availability and its ability to handle large spaces and mild to moderate occlusions. The handheld device is instrumented with an active tag that constantly emits its identity at very high frequency bands (5.8-7.2 GHz). Sensors placed in the environment detect these signals and triangulate their location based on the signal's time and angle of arrival. The advertised average accuracy of the system is 10-15 cm. However, after modifying the tag's antenna and strategically placing the sensors in the space, we obtained average accuracies of 7 cm in all directions. We instrumented a 10 m x 15 m space using six ultra-wideband sensors. We placed more sensors in the areas where there were more occlusions and thus a greater potential for multi-path reflections (*e.g.*, around desks, structural supports, etc).

#### 4.2 3D Orientation

The iCam system accomplishes absolute orientation with an Aichi Mi AMI201 3-axis magnetic compass and an Analog Devices ADXL series 2-axis accelerometer. The compass determines the handheld's azimuth or bearing angle and the accelerometer determines the tilt and roll angles. Because magnetic compasses are only accurate when held parallel to the ground (perpendicular to the gravitation axis), the accelerometer and the third magnetic axis provide a means to compensate for the tilt and roll angles and keep the compass electronically gimballed regardless of level. This allows the user to freely move the handheld and still obtain very accurate bearing information.

A common problem indoors is the magnetic interference produced by some consumer electronic devices. The iCam mitigates this problem by constantly monitoring the magnetic values in all directions and dynamically subtracts out any abnormal readings. iCam accomplishes its dynamic calibration by comparing the current magnetic values with that of the calibration data and the history of readings up to that point.

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<sup>2</sup> The 10 cm is an average estimate for the error in our instrumented space of 10 m x 15 m and interacting at distances of up to 5 meters. This value would increase for much larger spaces because of potential angular errors.

### 4.3 3D Range-finding

By coupling the handheld's position and orientation with its distance from an object, it is possible to determine the 3D position of that object. We do this by using the camera to track the red dot produced by the onboard laser pointer. We chose the laser tracking approach over ultrasound for two reasons. First, we already had plans to use a laser pointer for visual feedback, thus it was natural to leverage its capability. Secondly, ultrasound is not collimated enough to aim precisely at a small surface.

The laser diode is mounted at a known fixed position parallel to the camera (see Figure 4). The iCam projects a laser beam onto an object in the field of view of the camera. The onboard camera captures the dot from the laser along with the rest of the scene and a simple algorithm runs over the image looking for the brightest pixels. We then calculate the range to the object based on where along the vertical axis of the image this laser dot falls. The closer the dot is to the center of the image, the further away the object is. The distance is calculated using the angle between the camera's central focal point and the position of the dot in the camera's view.

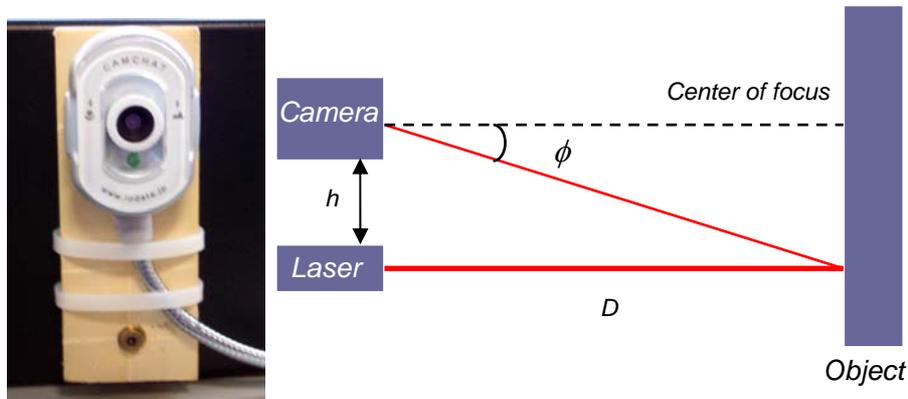
The equation used for this distance is:

$$D = \frac{h}{\tan \phi},$$

$$\phi = C * P$$

where  $h$  is the distance between the camera and laser diode, and  $\phi$  is the number of pixels from dot to center multiplied by the radians per pixel constant (C) and is proportional to the number of pixels from the center of the focal plan (P). The radians per pixel constant is derived in the lab through a series of calibration sequences with known distances  $D$ .

Since the laser dot only appears on the vertical axis near the center of the image, we limit the detection algorithm to only that region. This helps prevent false positives from other bright light sources that may appear in the image. This approach works reasonably well indoors with about 2 cm accuracy for distances between 1 and 5 meters. The accuracy and range are limited by the resolution of the image.



**Figure 4:** Left: Camera and laser diode mounted parallel to each other behind the iCam handheld. Right: Diagram showing the components of the distance equation stated previously.

#### 4.4 Calibration

The system requires two calibration steps: the orientation sensors on the handheld and then the location system in the environment.<sup>3</sup> To calibrate the orientation sensors, iCam prompts the user to hold the handheld level to the ground and then fully rotate it around all three axes.

Surveying and calibrating the Ubisense location sensors is a fairly time-consuming and tedious task. Since the sensors are mounted at an elevated position, it is difficult to measure absolute positions accurately between multiple sensors. Often, to find the proper setup it requires testing a couple different configurations. Thus, the overall process can be a very long task, involving the following steps:

- 1) placing the sensors in the environment
- 2) surveying the location of the sensors (both relative to the space and each other)
- 3) calibrating each of the sensors to known points in the environment

By leveraging the capabilities of iCam, we can combine the second and third steps and greatly ease the setup burden. After the user lays out the location sensors in the environment, he first selects one sensor as the reference, or origin, for the coordinate system. From any location that is in line-of-sight with the reference and any other sensor, the user aims the handheld at the reference sensor, taking care to keep the laser pointer on the sensor. After the user confirms the aim, the handheld generates  $X$ ,  $Y$  and  $Z$  values for the reference sensor using the ranging and orientation values from the handheld. These values are fed back into the calibration process. After the origin has been defined, the user remains in the same location and rotates the iCam, obtaining similar measures for the second sensor. The next step is to move to a different vantage point where the second sensor and a third, un-surveyed sensor is visible. The user gathers iCam measurements for this new pair of sensors from the new location. The user continues to

<sup>3</sup> The ranging system does not need to be calibrated because the needed values determined during construction do not change in different environments.

survey and calibrate the remaining sensors in the same pair-wise fashion. This procedure produces enough information to create a model of the sensor layout and, within a few minutes, the entire location system can be surveyed and calibrated.

#### 4.5 Overall system architecture

Figure 5 shows the overall system architecture. The position sensors in the environment are connected via network to a PC. The location software runs on that PC and transmits all resulting location information back to the iCam handheld device via 802.11b. The handheld computes its orientation and its range to other objects locally and then wirelessly transmits these values back to the PC. The handheld's application is written in Java and parts of the user interface (viewfinder and 3D overlays) are created using the OpenGL GL4Java extension. The geometric model and attributes of the physical and virtual space are stored on the PC, but are cached locally on the handheld during startup to speed up interaction. As the user modifies aspects of the space, the system updates the locally stored model and notifies the PC of the appropriate changes.

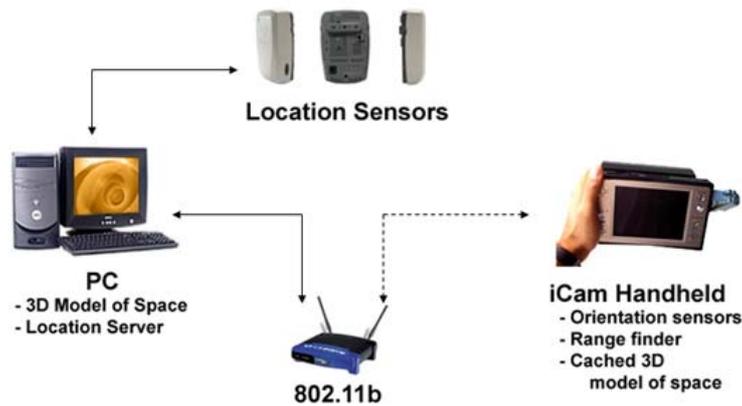


Figure 5: Overall system architecture of the iCam system.

## 5 Conclusions and Future Work

We have presented a handheld device called iCam that precisely determines its own location and orientation as well as the position of objects and surfaces in the physical environment. In addition to localizing itself and other objects, iCam serves as an interaction device for augmented reality applications. iCam offers several advantages over other similar devices. It provides accurate position information of both the handheld itself and a point in space indicated by a laser pointer. It uses a practical infrastructure of commercially available equipment to achieve this dual localization. iCam's simple mechanism for interaction between the physical and virtual space

facilitates an easy way to map the physical space. Finally, iCam simplifies the calibration of the location infrastructure by making it easier and faster. We have not previously seen a single device that can simultaneously and affordably accommodate calibration and content placement while also serving as a primary end user interaction device.

iCam's ability to accurately localize objects from a distance greatly simplifies the mapping process by allowing the users to define exactly what they intend *in situ*. We have demonstrated this by explaining how iCam would be used to place content for a location-aware tour guide, but this is certainly just the first step in exploring its capabilities. A system like iCam enables many other augmented reality applications that leverage the user's explicit intent and actions with the physical space. One can imagine other practical applications that take advantage of these capabilities. For example, suppose you are moving into a new space and are trying to decide where to place furniture. You have hired a moving company to handle the actual moving of the furniture, but you are unable to be there when the actual moving takes place. To ensure that the movers place the furniture where you need it to be, you can use iCam to mark spaces around the room where you would like the furniture placed (*e.g.*, trace a box around the south side of the room and attach a note with the text "black book-cases go here"). When the movers come to the space, they can then use iCam to view where you have designated the furniture to be placed.

The tour guide and the last example fall into the larger class groupware of applications that support asynchronous, collocated collaboration. Inventory location for customers (*e.g.*, helping someone find a book in a bookstore or a bottle of wine at a store) is another example. For individuals with mobility challenges, the precise, at-a-distance interaction can effectively extend their reach. These individuals, for example, could use iCam to indicate to caregivers where to find or place certain items around their home.

Authoring of location-aware content can be generalized to the description of behaviors that are associated to locations. Imagine developing a remote control that can point to a device and then control it. The "programmer" of the remote would need to indicate what physical space is occupied by the device, so that when a user points to that space subsequent control commands are sent to the correct logical device. This suggests a model of "programming the environment" in a very literal sense, and we see promise for this kind of use of location-enhanced at a distance interaction that can extend other recent work in programming simplifications for Ubicomp [7, 13].

These applications require simultaneous knowledge of the user interface's own location and orientation as well as the position of objects and surfaces in the physical environment. Our iCam device enables exploration of this kind of sophisticated location-aware experience, both from the user and developer perspectives. Among those tasks that are made easier are overall system calibration, creation of a map of the physical environment, and attaching virtual information to physical locations.

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