Towards LuxTrace: Using Solar Cells to Measure Distance Indoors

Julian Randall, Oliver Amft, and Gerhard Tröster

Wearable Computing Laboratory, IfE,
ETH Zürich, Switzerland
{randall, amft, troester}@ife.ee.ethz.ch

Abstract. Navigation for and tracking of humans within a building usually implies significant infrastructure investment and devices are usually too high in weight and volume to be integrated into garments.

We propose a system that relies on existing infrastructure (so requires little infrastructure investment) and is based on a sensor that is low cost, low weight, low volume and can be manufactured to have similar characteristics to everyday clothing (flexible, range of colours).

This proposed solution is based on solar modules. This paper investigates their theoretical and practical characteristics in a simplified scenario. Two models based on theory and on experimental results (empirical model) are developed and validated.

First distance estimations indicate that an empirical model for a particular scenario achieves an accuracy of 18cm with a confidence of 83%.

1 Introduction

Solar cells and modules are usually applied to the conversion of radiant to electrical energy. However, as we show in this paper, such energy flows may also be considered as data flows, thus extending solar module functionality to a form of receiver. Data can be transmitted for reception by solar modules via IR [1] as well as via fluorescent tubing [2]. In the concept proposed here, the solar modules are used only to track the intensity of indoor radiation (e.g. lights) as a form of context information. By using existing lights infrastructure, investment is minimised. Taking the taxonomy of position estimation approaches of Fox [3], we therefore have a local (e.g. single building) and passive (not transmissive) approach. Conceptually, the solar cells are "outward looking" and measure multiple beacons in the environment.

To the authors' knowledge, such a use of solar modules as a component of a location tracking system has not been previously investigated. Optical location investigations have previously considered various technologies including infra red [4, 5], laser [6, 7] and video [8, 9, 10, 11]. Further location technologies [12], include inertial [13], ultrasound [14], RF [15] and magnetic [16]. It has also been shown that such technologies can be used in tandem [17, 18]. A solar *powered* location system is the MIT Locust [19].

T. Strang and C. Linnhoff-Popien (Eds.): LoCA 2005, LNCS 3479, pp. 40–51, 2005.

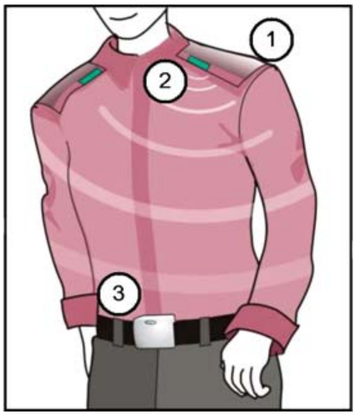

Fig. 1. LuxTrace concept: Wearable location tracking by solar cells

In this paper, a scenario of an office worker walking in a corridor is considered with solar modules integrated into the shoulder area of their clothing. Such modules can have similar characteristics to textiles e.g low cost (2$), low weight (20g), low volume ($2cm^3$) and with a range of colours. A potential concept is shown in Figure 1 in which the flexible solar module system on the shoulder (1) transmits one or more RF pulses only when there is sufficient energy to do so i.e. beneath a light source. This data is collected and processed by the belt worn computer (3) [20]. The environment is assumed to be static [3] as the lights in the corridor are always on during office hours. Whilst it is necessary to process the data from the solar modules, their relatively low bit rate is well adapted to on body processing such as with a body worn computer. Sensors other than solar cells may also be necessary for satisfactory location tracking.

This paper is structured as follows. The investigation of the office worker scenario firstly considers radiant energy received by a solar module from a theoretical perspective. A single fluorescent light tube is modelled from which the radiant energy in a number of interconnected corridors is extrapolated. This model is then validated using a solar module mounted on a wheeled vehicle. The same vehicle is then used to collect training data from which a second model is developed that is specific to similar corridors. The second model is then validated using further data. In the discussion the LuxTrace concept is analysed.

2 Simulation

2.1 Irradiance Modelling

Typical office buildings have windows, varying room architecture, colouring and various ambient light sources, which influence the light intensity and frequency components. These parameters may provide information for location estimation, when included in a radiant energy map and used as reference during indoor navigation. In this first approach, we rely on information extracted from artificial light sources only. More precisely, we consider in this analysis a hallway scenario equipped with regular fluorescent light tubes installed in the ceiling at 2.5 meters from the floor.

Theoretical Model. The source of radiant energy (emitter) creates a field of radiant flux. Many emitters can be modelled as a point source at sufficient distance. The total received flux per area is called *Irradiance* (W/m^2). For the following model, a fluorescent light tube will be approximated as a bounded concatenation of point sources.

As the distance between fluorescent light tube and photovoltaic solar cell (receiver) changes, so does the light intensity received at the cell (irradiance). Irradiance I_{RPS} at a distance r from a point source emitting radiant energy with intensity I_0 is related by the inverse square law [21]:

$$I_{RPS} = \frac{c * I_0}{r^2} \qquad \text{with } c = const. \text{ and } I_0 = const. \tag{1}$$

For positioning in three-dimensional space the coordinate system x, y, z shown in Figure 2 will be used, with its origin at the centre of the tube $\underline{0}(x_0, y_0, z_0)$.

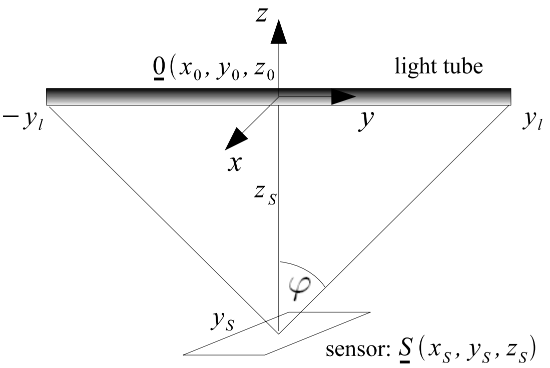

Fig. 2. Schematic for the theoretical model

In the particular case, where a receiver is positioned on a plane with $z_S = const.$ near to the light tube, the irradiance is at maximum, if $x_S = x_0$ and $y_S = y_0$. This can be described as the total planar irradiance I_{TPS}. In the general case, for the irradiance at the solar cell sensor I_{SPS} an arbitrary angle φ must be considered, with $-90° \leq \varphi \leq 90°$ between the point source emitter and the receiving sensor, related by the cosine law: $I_{SPS}(\varphi) = I_{RPS} * cos(\varphi)$.

The distance $\underline{r}$ can be decomposed in the coordinate system by the three coordinates positioning the solar cell $\underline{S}(x_S, y_S, z_S)$ (Figure 2) depending on the position along the light tube (y-coordinate):

$$r(y) = \sqrt{{x_S}^2 + (y_S - y)^2 + {z_S}^2} \tag{2}$$

The cell irradiance from a point source I_{SPS} can be directly related to the coordinate system, by inserting equation 2 into equation 1:

$$I_{SPS}(y) = \frac{c * I_0 * z_S}{({x_S}^2 + (y_S - y)^2 + z_S)^{3/2}} \tag{3}$$

This relation can be used to simulate the irradiance from a solar cell movement in any direction under light sources at arbitrary heights. The total irradiance I_S for a fluorescent light tube is found by integrating over the chain of point sources (equation 4) in y-direction:

$$I_S = \int_{-y_L}^{y_L} I_{SPS} \quad \mathrm{d}y \quad = \int_{-y_L}^{y_L} \frac{c * I_0 * z_S}{({x_S}^2 + (y_S - y)^2 + z_S)^{3/2}} \quad \mathrm{d}y \tag{4}$$

The distance to the light source, e.g. z-component z_S of $\underline{S}$ is assumed as being constant. From the perspective in x-direction, the model assumes the light tube as a point source. Hence, x_S is constant. The total length of the light tube is denoted by l. Hence, the integration limits are described by $y_L = l/2$. I_S is derived in units of W/m.

Practical Data Acquisition. The change in irradiance when varying the distance of a photovoltaic solar cell to the light emitter can be monitored by current or voltage variation. Whilst current is directly proportional to irradiance, voltage is less affected. It varies with the log of intensity:

$$V \propto ln(I_S)$$

For convenience of signal acquisition, solar cell voltage across a 10kΩ resistance was tracked. This resistance is sufficient in our case to ensure that voltage was almost directly proportional to current (and irradiance) [22].

The log correction made does not change the general shape of the waveforms. The resulting simulation graphs are depicted in Figure 3. For the simulation, $c = 1$ and $I_0 = 5W/m^2$ is used. These values are fitted with real measurements to reflect size and type of the solar cells in the model. Since for this simulation example the y-component of the movement is $\Delta y = 0$, the light tubes are approximated as point sources.

Detection of Light Emitter. Figure 3 shows the expected waveform for a straight trajectory equidistant to the walls down a corridor. The light tubes are oriented at right angles to the trajectory and regularly distributed (see Figure 2). Assuming a typical office building height of about 2.5 meters, the distance z_S from an adult shoulder to the ceiling mounted light sources will be about one meter or less. The regular distance d_L between the light tubes is greater than 2.5 meters. Using the theoretical model for the case of $d_L = 2.5m$ and $z_S = 0.8m$ there is a difference of 20% in the log irradiance from the minimum to maximum value. Such a difference is sufficient to detect when the solar module is beneath the tube.

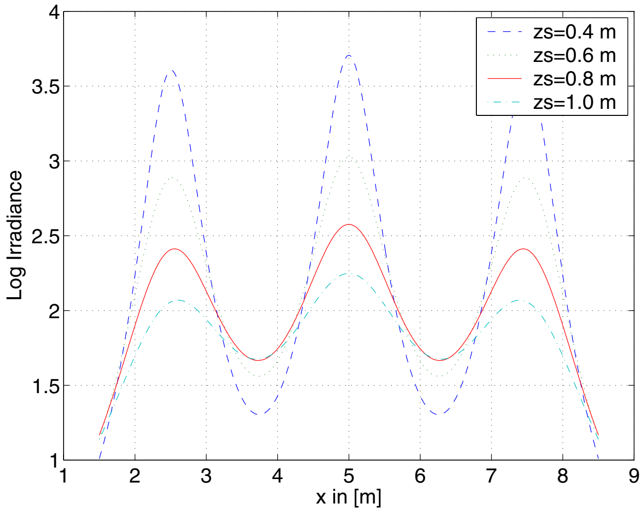

Fig. 3. Log corrected irradiance from three point sources at different ceiling heights

2.2 Environment Effects and Theoretical Model Limitations

The theoretical model does not consider indirect light, such as reflections at walls and cupboards. Fortunately indirect light generally has an order of magnitude less intensity than direct light, so this component of radiant energy has not been included in the theoretical model.

The case of occluded direct light is familiar because it creates distinct shadows hindering radiant energy reaching a sensor. For the intended application using overhead light sources, the possible obstruction area is limited to objects in direct connection with the light source, e.g. the box frame supporting the fluorescent light tube or objects in the line of sight above the solar cell. As this model does not cover human aspects in detail, the head as a possible obstacle is not considered.

2.3 Theory Based Distance Model

In a second modelling step, a 3-dimensional environment for configurable light distributions has been built for the majority of the corridors of our offices. With this approach it is possible to simulate various building scenarios. It is used here exclusively for a section of the corridor scenario.

For the following analysis a distribution of fluorescent light tubes according to the simulated irradiance map in Figure 4 has been chosen. This situation reflects part of a hallway from an existing office building. The scene consists of one long walkway leading to offices and a connecting passage. The section has 3 identical light tubes, equidistant with both walls, oriented in a perpendicular direction to the main corridor access. The distance between the lights is $d_L = 3.7m$. There are no windows or other significant sources of artificial light in the the scenario.

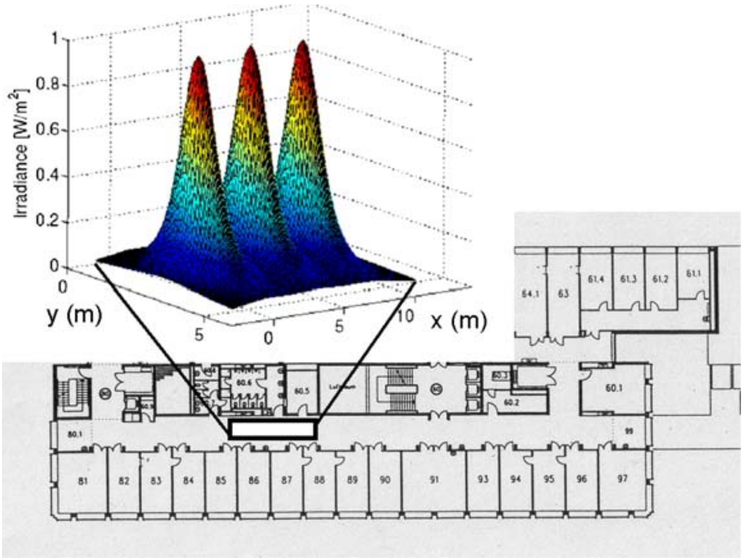

Fig. 4. Example of a simulated irradiance distribution as 3D plot for the scenario

3 Experiments

The initial goal of the experiments was to verify the waveforms calculated in the simulation. At the same time, measurement data were acquired for creating and validating a trained model. This section details the measurement system used and the data sets acquired. Experiments were carried out within the corridor in which radiant energy had been simulated.

3.1 Sensing System

A measurement system based on a trolley (see Figure 5) was built that allows acquisition of the voltage from solar cells. The same set up was used for all experiments. The solar module was positioned in a horizontal plane on top of the trolley. Furthermore, a relatively constant distance z_S between cell and fluorescent light tubes could be maintained, varying by a few millimetres due to ground roughness under the wheels of the trolley for example.

The photovoltaic solar module used for the experiments is an amorphous silicon thin film deposited on glass[1]. The voltage of the solar cells was acquired at 1kHz and 12 bit resolution using a standard data acquisition system.

To associate the acquired waveforms with actual distance down the corridor, two approaches have been used: By using markers on a precisely measured straight trajectory, the waveforms have been tagged. This measurement is con-

---

[1] Manufacturer: RWE SCHOTT Solar, model: ASI 3 Oi 04/057/050.

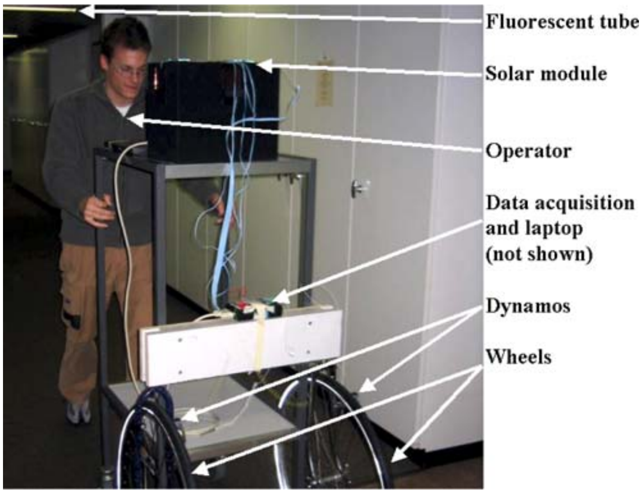

Fig. 5. Measurement trolley used for acquiring solar cell voltage

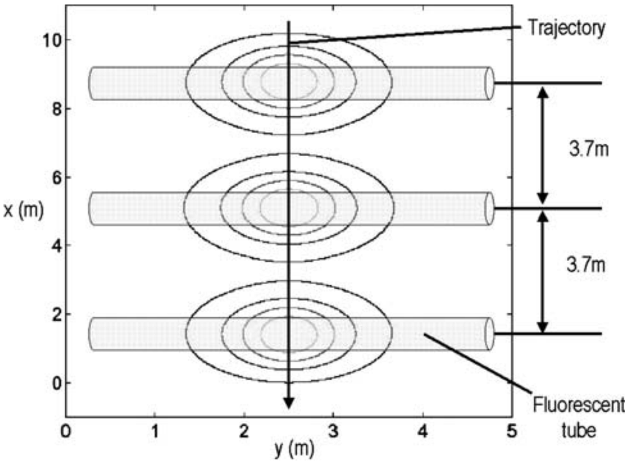

Fig. 6. Experiment setup: Movement on straight line under light tube centre

sidered as being relatively precise but limited in resolution, since data could only be collected practically every 50cm. Therefore a second distance measurement method based on a bicycle dynamo and bicycle wheel appropriate was used. A peak detection of the acquired voltage waveform from the dynamo generator was used to determine the system speed. The accuracy of the wheel measured distance compared with the actual distance was always over 98%. Since this result indicates satisfactory accuracy, the second method was used to acquire ground truth for subsequent experiments.

3.2 Description of Experiments

The experiments were performed pushing the trolley at constant walking speed ($0.55ms^{-1}$). A straight trajectory was taken below the middle of the light tubes as shown in Figure 6. The distance between the horizontal solar cell and the fluorescent light tubes was $z_S = 73cm$, the distance between the light tubes was $d_L = 3.7m$.

Irradiance at the solar module was measured over trajectories with distances in the range of 2m to 10m. Each time the solar module passed under a tube, a waveform peak was measured. A total of 14 such peaks were recorded.

4 Results

4.1 Theoretical Model Validation

The theoretical model used varied over the range of 0.4V to 3.3V whilst the average of the measured values was in the range 0.1 to 2.7V. The error for ten peak waveforms (see Figure 7) was less than 0.3V with a confidence level of 81%. Part of the error can be attributed to the theoretical model being for a bare fluorescent light tube rather than the measured data which was for an installed light tube including a reflective housing.

4.2 Distance Estimation

Distance information can be extracted from the amplitude of the waveform by using a mapping between voltage and known distance from training data. To

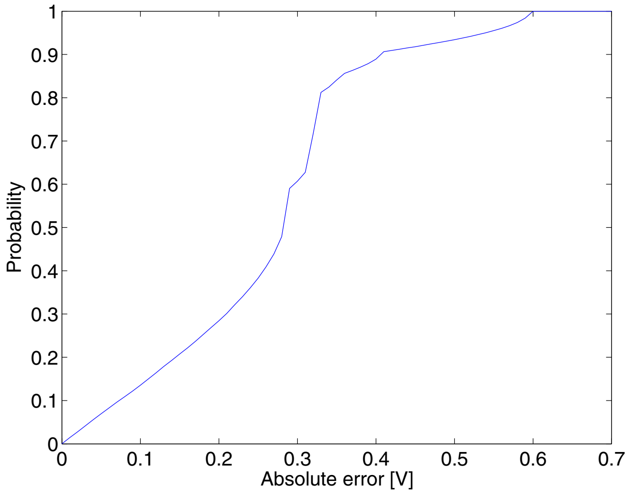

Fig. 7. Cumulated error of the simulation model compared to the average measured voltage

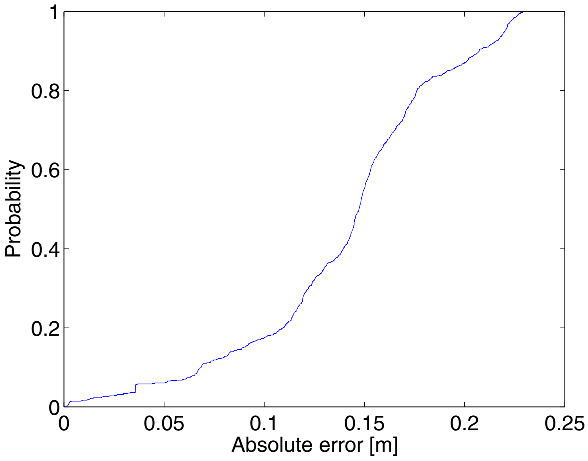

Fig. 8. Cumulated error of estimated distance by the empirical model

build the model, training data sets were segmented into single peak waveforms and scaled to the known light to light distance of $d_L = 3.7m$. This empirical model was used in a simple mapping function which relates observed voltages from the solar cell and the average distance under the light source.

Since the minimum and maximum amplitude of the test data varied in the range of ±10%, the empirical model did not provide information if the amplitude was greater or less than the average curve. To improve the estimation, the last available averaged speed information obtained with the same model was used in these periods, without information from mapping, to support the distance estimation. The average distance estimation error obtained with this method is less than 18cm with a confidence of 83% over a distance of 7.4m (see Figure 8).

5 Discussion

The assessment of whether solar modules could contribute to a location tracking system can be based on relatively standardised topics. A location system assessment taxonomy proposed by Hightower [23] includes scalability, cost, recognition and limitations.

Scalability of the solar module system will depend on a number of factors including amount of area with no distinct light source and superposition of radiant energy from different sources. Another aspect that we consider as part of *scalability* is the number of sensors. Given the relatively low cost of the solar cells, it can be anticipated that a number of sensors could be used for each user. It would then be possible with non co-planar solar modules positioned on the user to support trilateration.

The *cost* of the solar module system is a function of installation and maintenance. Indoors, lights and on body computers (e.g. mobile phone) are generally available; therefore the incremental hardware will only be the sensor node(s). Installation software costs might include a location tracking program and a simplified map of the building including light source locations. Incremental maintenance costs of the system would be zero assuming that lighting infrastructure is not changed and bulb replacement service(s) exist.

Recognition of the user context may be enhanced both by collecting further data from the solar modules (e.g. light sources can be distinguished by frequency and spectra) as well as including complementary sensors. A simple example of a complementary sensor is an accelerometer or pedometer that would provide information about user movement when he or she is not under sufficient incident radiant energy.

Limitations of using solar modules for optical measurements compared with using a charge coupled device (CCD) camera are much lower pixel rates. These rates may be partly mitigated by the use of lateral effect photo-diodes [24, 25]. Another mitigating factor with solar modules is their lower response times compared with CCDs. Sensor response time can be important in virtual reality applications for avoiding user nausea [26]. Further limitations are mentioned in [22].

6 Conclusion and Future Work

In this paper, the LuxTrace concept of using solar cells as sensors has been presented and one kind of solar cell characterised. For a scenario representative of an office worker walking down a corridor, distance moved has been determined within 18cm with a confidence level of 83%. The results provide evidence that distance travelled and therefore instantaneous speed of a moving object can be estimated satisfactorily using only the output of solar cells and a model based on theory or acquired waveforms (empirical model). Indirectly these results also support the case that a garment integrated location tracking system will be achievable.

Based on these encouraging results, we intend to investigate a number of further avenues. Both models are rudimentary and could be improved or replaced by models based on probabilistic algorithms for example. Also, as solar modules are low cost, a number of them could be used simultaneously in future experiments to allow the estimation of orientation for example. Experiments with alternative (flexible) solar cells, such as manufactured by VHF technologies [27], integrated into clothing would enable location systems embedded into garments as well as allow the influence of gait to be investigated. Finally, whilst the physical limits of what can be achieved with solar modules are an intrinsically valuable result, solar modules could also be combined with further (location tracking) technologies.

Acknowledgement

Thank you to Martin Burri and Christian Morf for performing experiments and preparing a number of figures. We are also grateful to Stijn Ossevoort for proposing the name *LuxTrace* in particular.

References

1. Nishimura, T., Itoh, H., Nakamura, Y., Yamamoto, Y., Nakashima, H.: A compact battery-less information terminal for real world interaction. In: Pervasive Computing: Proceedings of the International Conference. (2004) 124–139
2. Talking Lights: Talking Lights, Boston MA USA. (http://www.talking-lights.com/how.htm)
3. Fox, D.: Markov Localization: A Probabilistic Framework for Mobile Robot Localization and Navigation. PhD thesis, Institute of Computer Science TU Dreseden Germany (1998)
4. Want, R.; Hopper, A.: Active badges and personal interactive computing objects. Consumer Electronics, IEEE Transactions on, Vol.38, Iss.1 (1992) 10–20
5. Ward, M., Azuma, R., Bennett, R., Gottschalk, S., Fuchs, H.: A demonstrated optical tracker with scalable work area for head-hounted display systems. In: Proceedings of the symposium on Interactive 3D Graphics. (1992) 43–52
6. Evans, J., Chang, T., Hong, T., Bostelman, R., Bunch, W.: Three dimensional data capture in indoor environments for autonomous navigation, NIST Internal Report 6912. Technical report, (www.isd.mel.nist.gov)
7. Sorensen, B., Donath, M., Yang, G.B., Starr, R.: The Minnesota Scanner: a prototype sensor for three-dimensional tracking of moving body segments. (Robotics and Automation, IEEE Transactions on, Vol.5, Iss.4) 499–509
8. Piscataway, N.: Multi-camera multi-person tracking for Easy Living. In: 3rd IEEE Int'l Workshop on Visual Surveillance. (2000) 3–10
9. Thrun, S., Bennewitz, M., Burgard, W., Cremers, A., Dellaert, F., Fox, D., Haehnel, D., Rosenberg, C., Roy, N., Schulte, J., Schulz, D.: Minerva: A second generation mobile tour-guide robot. In: Proc. of the IEEE International Conference on Robotics and Automation (ICRA'99). (1999)
10. Starner, T., Maguire, Y.: A heat dissipation tutorial for wearable computers. In: Digest of Papers. (1998)
11. Zobel, M., Denzler, J., Heigl, B., Nöth, E., Paulus, D., Schmidt, J., Stemmer, G.: Mobsy: Integration of vision and dialogue in service robots. In: International Conference on Computer Vision Systems (ICVS). (2001) 50–62
12. Tauber, J.A.: Indoor location systems for pervasive computing. Technical report, Theory of Computation Group Massachusetts Institute of Technology (2002)
13. Vildjiounaite, E., Malm, E.J., Kaartinen, J., Alahuhta, P.: Location estimation indoors by means of small computing power devices, accelerometers, magnetic sensors, and map knowledge. In: Pervasive '02: Proceedings of the First International Conference on Pervasive Computing, Springer-Verlag (2002) 211–224
14. Ward, A., Jones, A., Hopper, A.: A new location technique for the active office. IEEE Personnel Communications, 4(5) (1997) 42–47
15. Bahl, P., Padmanabhan, V.N.: Radar: An in-building RF-based user location and tracking system. In: INFOCOM. (2000) 775–784

16. Rabb, F.H., Blood, E., Steiner, T.O., Jones, H.R.: Magnetic position and orientation tracking system. IEEE Transaction on Aerospace and Electronic Systems, AES-15(5) (1979) 709–718
17. Lee, S.W., Mase, K.: A personal indoor navigation system using wearable sensors. In: Proceedings of The Second International Symposium of Mixed Reality (ISMR01), Yokohama. (2001)
18. Randell, C., Muller, H.: Low cost indoor positioning system. In Abowd, G.D., ed.: Ubicomp 2001: Ubiquitous Computing, Springer-Verlag (2001) 42–48
19. Starner, T., Kirsch, D., Assefa, S.: The Locust Swarm: An environmentally-powered, networkless location and messaging system. In: 1st International Symposium on Wearable Computers. (1997) 169–170
20. Amft, O., Lauffer, M., Ossevoort, S., Macaluso, F., Lukowicz, P., Tröster, G.: Design of the QBIC wearable computing platform. In: Proceedings of the 15th IEEE International Conference on Application-specific Systems, Architectures and Processors. (2004)
21. Randall, J.: On the use of photovoltaic ambient energy sources for powering indoor electronic devices. PhD thesis, EPFL Lausanne Switzerland (2003)
22. Amft, O., Randall, J., Tröster, G.: Towards LuxTrace: Using solar cells to support human position tracking. In: Proceedings of Second International Forum on Applied Wearable Computing, Zrich, CH, 17-18th March 2005. (2005 to appear)
23. Hightower, J., Borriello, G.: A survey and taxonomy of location systems for ubiquitous computing. IEEE Computer, 34(8) (2001) 57–66
24. Pears, N.: Active triangulation rangefinder design for mobile robots. In: Proceedings of the 1992 IEEE/RSJ International Conference on Intelligent Robots and Systems. (1992)
25. Pears, N.: An intelligent active range sensor for vehicle guidance: system overview. In: Proceedings of the 1996 IEEE/RSJ International Conference on Intelligent Robots and Systems, Vol.1. (1996)
26. Janin, A.L., Zikan, K., Mizell, D., Banner, M., Sowizral, H.A.: Videometric head tracker for augmented reality applications. In: Proc. SPIE Vol. 2351, p. 308-315, Telemanipulator and Telepresence Technologies, Hari Das; Ed. (1995) 308–315
27. VHF Technologies: Flexcell from VHF Technologies, Yverdon-les-Bains Switzerland. (http://www.flexcell.ch)