Towards LuxTrace: Using solar cells to support human position tracking

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Abstract. Tracking the position of humans within a building usually implies significant infrastructure investment; also devices are usually too high in weight and volume to be integrated into garments.
We propose a system that relies on existing infrastructure (and therefore 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).
The proposed contribution to this area is based on solar modules. This paper investigates their theoretical and practical characteristics in a simplified scenario. Forward motions on the large scale up to 10m long as well as small scale motions related to the human body on the spot of less than 10cm are investigated. Models with accuracy in the centimetre range have been achieved.
The case that energy harvesting technology could be used for both sensing and providing power is thus strengthened.

1 Introduction

Most indoor location or motion aware systems require the user to carry devices that have not yet been integrated into clothing. This lack of integration can partly be attributed to these components falling short on specification for garments with respect to factors such as cost, weight, volume, mechanical flexibility and colour. In this paper we propose a contribution to context awareness that can satisfy garment specifications as well as provide information about certain user activities.

The partial solution proposed in this paper is based on solar modules being used to measure changing light levels while manoeuvring in buildings. The example of the *LuxTrace* concept in Figure 1 shows a flexible solar module on the shoulder (1) that is connected to a low power transmission (e.g. RF pulses only) system (2). This data is collected and processed by (3) the belt worn wearable computer [1]. The name *LuxTrace* is based on lux for light and trace for sensing and recording. We use the name LuxTrace in the title of a number of papers and reports to draw attention to their complementary nature.

Whilst solar cells are more usually applied for energy harvesting it is envisaged that future applications would also collect data from the environment. In

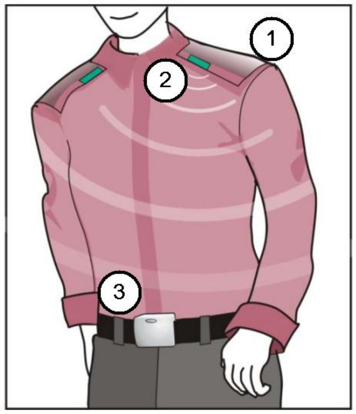

Fig. 1. LuxTrace concept: Wearable location tracking by solar cells

this way we seek to demonstrate that energy harvesting technologies may be used as valuable sources of data as well as power. Such a progress could support the development of energy autonomous embedded sensors.

Solar modules as sensing components of position aware systems have not been previously investigated. Optical location investigations have previously considered various technologies including infra red [2, 3], laser [4, 5] and video [6–9]. Further location technologies [10], include inertial [11], ultrasound [12], RF [13] and magnetic [14]. It has also been shown that such technologies can be used in tandem [15, 16]. A solar *powered* location system is the MIT Locust [17].

Potential uses of solar cell position data can be imagined in a number of environments such as hospitals, factories and offices especially where system security is less important than cost criteria. Such environments generally have overhead lighting on in the corridors at all times, which implies that incremental infrastructure for the solar module system would not necessarily be required.

As an example in a hospital or hotel, solar modules could be used to track overhead lights to support guiding new arrivals to their correct room. In a flexible factory with a number of manufacturing cells, solar modules on staff clothing could be used to help record how long a process took (relatively little light change at a workplace), or how much time was needed to move to the next process (more light change as the individual moves under a number of lights) in order to support work planning and/or billing.

In the initial evaluation of solar modules as positioning sensors we investigated horizontal translations up to 10m as an example of large scale motions. Given the promising results from the latter experiments, we then investigated a small scale motion of less than 10cm. This difference in range forms the basis for the two part structure of this paper. In the first part, for meter scale horizontal translations in a known environment, we report an empirical model trained for a specific office corridor that achieved an accuracy of 18 cm with a confidence level of 83%. In the second part of the paper, we measure the displacement at the shoulder of a human walking at a fixed location on a treadmill under constant overhead lighting. Simultaneous measurements with a solar cell and a accelerometers were used to evaluate a human motion model.

2 Part 1: Meter-scale horizontal translations

The goal of the horizontal translation experiment was to investigate the accuracy of distance measurement by a solar cell moving in a plane parallel with the floor of an office corridor.

2.1 Experiments

A wheeled trolley as shown in Figure 2 was used for the horizontal translation experiments. The distance travelled by the trolley was established by odometry based on two bicycle wheels equipped with dynamos on the two forward corners of the trolley. The output peaks from the latter electric motors were counted and found to be directly related to distance moved with an accuracy greater than 98%.

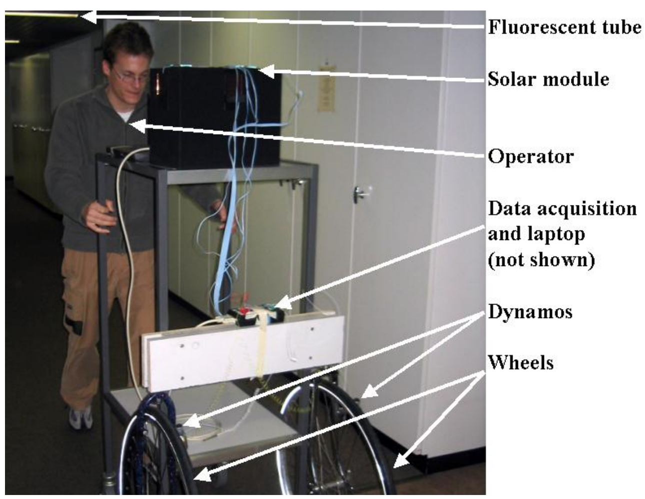

Fig. 2. Measurement trolley used for acquiring solar cell voltage in horizontal translation

The photovoltaic solar module used for the experiments is an amorphous silicon thin film deposited on glass[1]. The voltage of the horizontal mounted solar cell was collected across a 10kΩ resistance at 1kHz and 12 bit resolution using a commercial data acquisition system.

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

For the range of radiant intensity experienced indoors (typically less than 2 W/m^2), it can be seen from Figure 3 that given the resistance used, the voltage from the solar cell can be expected to be almost directly proportional to current. The figure shows that the V=IR linear trace always subtends the I-V curves where current is almost constant. Given that solar cell current and radiant intensity are directly proportional over a much wider range than will be considered here, for the purposes of this paper, voltage will be taken as having a linear relationship with radiant intensity.

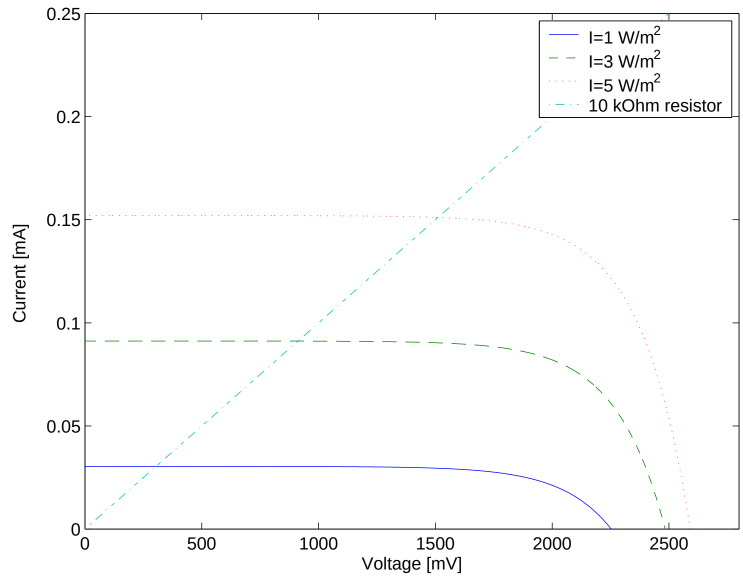

Fig. 3. Current-voltage (I-V) curves for the solar cell used in these experiments compared with resistance properties (V=IR)

Experiments were performed in an office corridor. The lighting along the corridor was assured by regularly (d_L = 3.7 m) spaced fluorescent tubes that were switched on at all times. These tubes were integrated into the ceiling and oriented perpendicular to the walls of the corridor. The light diffusers were made of grooved (principle of Fresnel) colourless perspex. The distance between the solar module on the trolley and the diffuser was 73 cm.

A straight trajectory down the middle of the corridor was taken at a constant walking speed. Throughout the experiment the solar module was kept equidistant from the ends of the fluorescent tubes i.e. parallel to the corridor as shown in Figure 4.

The solar module voltage across the resistance was collected over trajectories with varying length in the range of 2 m to 10 m. Each time the solar module passed under a tube, a waveform peak was measured, 14 of which were recorded.

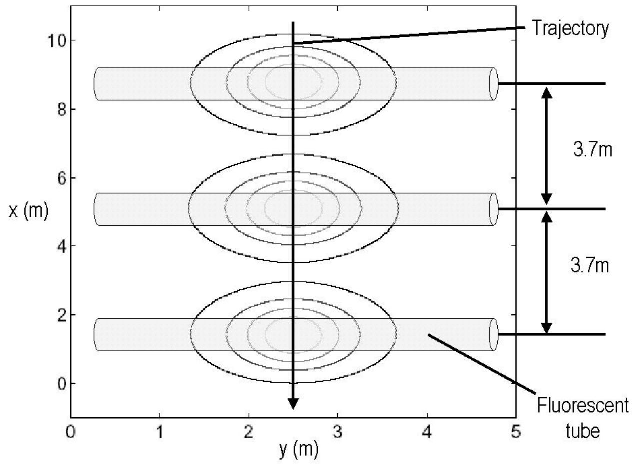

Fig. 4. Trajectory of solar module under the overhead tubes (tubes not to scale)

A model specific to the office corridor was developed to investigate the relationship between intensity and distance [18]. Firstly the data from the 14 peaks were separated into ($d_L = 3.7$ m) peak to peak segments. The average voltage for each distance was calculated. The resulting average curve was used in spline form to relate observed voltage with distance between successive light tubes. As the minimum and maximum voltage of the test data varied in the range of 10%, the corridor specific model did not cater for voltage greater or less than the average curve. To improve the estimation, the last available averaged speed from the model was used.

2.2 Results

The voltage (and therefore intensity) was found to vary as shown in the Figure 5. The peaks (at distances 0, 3.7 and 7.4 m) matched the position of the light tubes.

The corridor specific model was validated by repeating the experiment shown in Figure 4. The average distance estimation error obtained between the odometric system and the model was less than 18 cm with a confidence of 83% over a distance of 7.4 m (Figure 6).

3 Part 2: Centimetre scale human shoulder motion

The goal of the centimetre scale human motion experiments was to show that more detailed human motion than horizontal translation could be detected using solar cells. The shoulder was selected for placing the solar cell as we believe that this body position would be optimal with respect to maximising energy collected

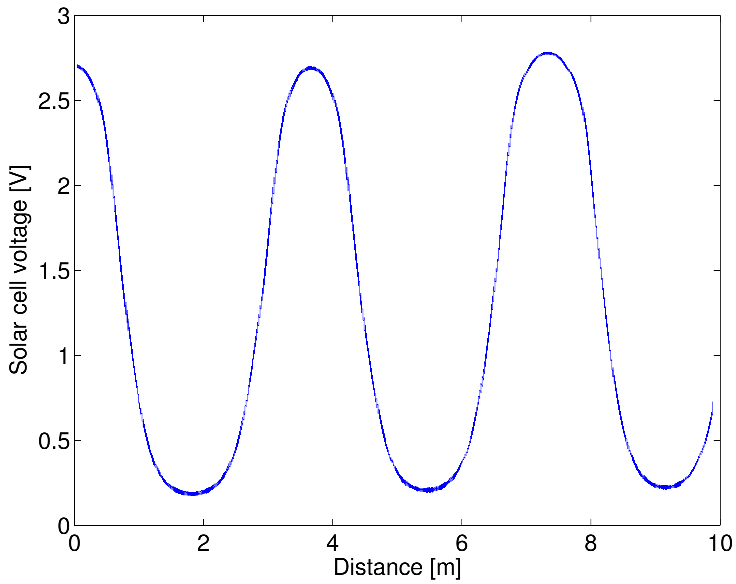

Fig. 5. Typical intensity trace measured in the trajectory described in the experimental procedure (as shown in Figure 4)

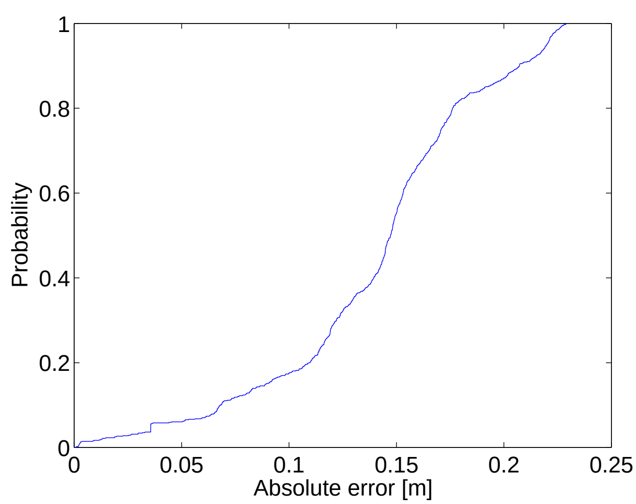

Fig. 6. Cumulated distribution function for the error between the corridor specific model and the odometric system

by the solar cell as well as ensuring optimal recognition of overhead lighting since there would be less likelihood of obstruction from other parts of the body. We also sought to quantify the effect of human walking motion as this would be a perturbation of a garment based distance measuring system.

3.1 Perpendicular sinusoidal model of shoulder displacement during walking

The displacement of a point on the human shoulder ignoring horizontal translations (locomotion) is less than 10 cm. A point on the human shoulder makes a movement while walking that resembles a U shape when viewed from the front; this is the case for speeds from 1.6-2.3 m/s [19]. This displacement can be modelled by an overlay of harmonic sinusoidal functions.

For the positioning in three-dimensional space the coordinate system x, y, z was used, with its origin at the light source. The x-axis describes the heading/walking of the user and the y-axis stretches from shoulder to shoulder (see Figure 7).

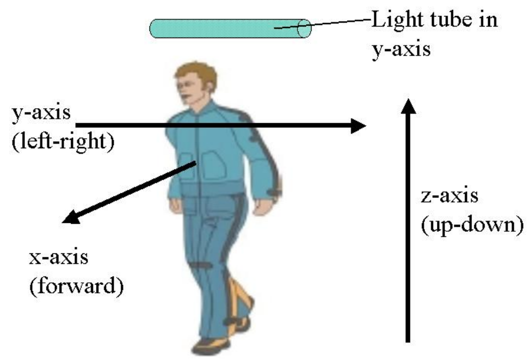

Fig. 7. Coordinate system used to describe displacement

The largest displacement for normal and higher walking speeds is found in the z-axis (up and down) and y-axis (left and right). The displacement in z is mainly due to the difference in height of the legs when parallel ("tallest") and furthest apart ("shortest"). In the coordinate system the z-axis displacement d_Z describes the vertical distance between a shoulder worn solar cell and the light source and can be approximated by a second order harmonic function:

$$d_Z = f_Z * sin(2\omega_0 t + \vartheta_Z) \qquad \text{with } \omega_0 = \frac{2\pi}{T} \tag{1}$$

where T is the gait stride period; ϑ_Z is the phase and f_Z is the z-axis amplitude depending on walking speed v. We refer to the stride period as the time from initial contact of one foot to the following initial contact of the same foot.

The y- displacement can be associated with the side to side sway of the shoulders, known to be more noticeable in males than females [20]. This sway can be understood as an upturned sprung pendulum with a fixed point at the body centre of mass. It can be estimated by a first order harmonic function:

$$d_Y = f_Y * sin(\omega_0 t + \vartheta_Y) \tag{2}$$

where accordingly ϑ_Y is the phase and f_Y is the y-axis amplitude depending on walking speed. Both ϑ_Z and ϑ_Y are kept constant since they influence walking symmetry and displacement marginally. For the purpose of this model, the displacement along x is not considered, since the relative influence on walking, compared to d_Z and d_Y is low. Moreover, from Figure 5, it can be seen that horizontal translations (in x-axis) have relatively little influence on voltage measured (and therefore intensity) within ±10 cm of the light tube which is the case we consider.

The functions f_Z and f_Y are derived empirically as linear regression functions from [19] based on the measurements done at five male subjects:

$$f_Z = 20 + 5 * speed \qquad \text{and} \qquad f_Y = 38 - 6 * speed \tag{3}$$

The combined oscillation of these two perpendicular sinusoidal functions resembles the U shape found in the frontal view (plane with x=const.) of shoulder motion [19]. Using the model, the displacement of the shoulder at different walking speeds can be estimated. The maximum absolute displacement at 1.4m/s is $\Delta d_Z = \pm 27mm$ and $\Delta d_Y = \pm 30mm$.

As the distance between light source and photovoltaic solar cell (receiver) changes, so does the light intensity received by the cell. Intensity 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]:

$$I_{RPS} = \frac{c * I_0}{r^2} \qquad \text{with } c = const. \text{ and } I_0 = const. \tag{4}$$

In the particular case, where a light sensor is positioned on a plane with $z_S = const.$ near to the light tube, the intensity is at maximum if $x_S = 0$ and $y_S = 0$. This can be described as the total planar intensity I_{TPS}. In the general case, for the intensity 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:

$$I_{SPS}(\varphi) = I_{RPS} * cos(\varphi) \tag{5}$$

The received light intensity from a point source I_{SPS} can be directly related to the coordinate system:

$$I_{SPS} = \frac{c * I_0 * z_S}{(y_S^2 + z_S^2)^{3/2}} \tag{6}$$

This relation can be used to simulate the intensity during solar cell movement in any direction under light sources at arbitrary heights. The model was validated as described in section 3.3. For the purpose of this model the coordinates are described by the relations 7 where z_0 and y_0 indicate the absolute position of the shoulder when standing.

$$z_S = z_0 - d_Z \qquad \text{and} \qquad y_S = y_0 - d_Y \tag{7}$$

3.2 Experiments

A healthy male subject (69kg) with body height 1.82m was selected who wore a close fitting T-shirt with Velcro sewn on the shoulders. The solar module used in Part 1 fixed onto his left shoulder and an acceleration sensor[2] was securely to the back at waist level. The setup is shown in Figure 8. The distance between shoulder and light tube while the subject was standing was 59cm.

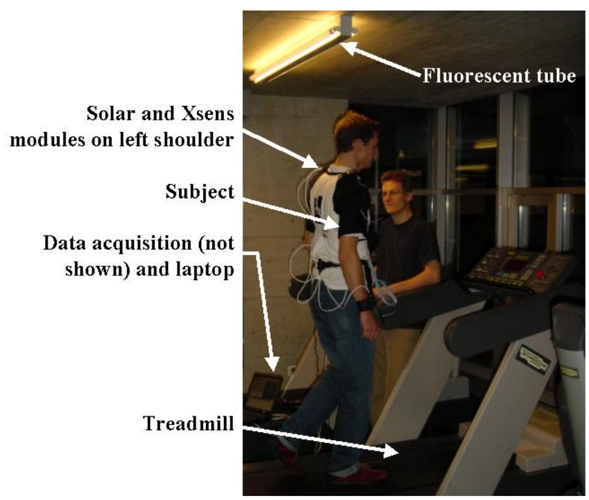

Fig. 8. Solar module and acceleration sensor fixed on the shoulder of the T-shirt worn by the experimental subject

The subject walked on a treadmill[3] that was running at a fixed speed. The subject's speed was kept constant by maintaining a relatively fixed position on the treadmill. The head was directly beneath a fluorescent tube similar to those

[2] Manufacturer: XSens Technologies B.V., model: MT9B
[3] Manufacturer: Technogym

installed in the corridor experiments. The subjects position was also equidistant from the ends of the fluorescent tube. Once the subject was comfortable with the speed, the solar module and acceleration sensors were synchronised and monitored for 1 minute. Data was collected for three speeds (0.28, 0.83, 1.39 and 2.78 m/s) of the treadmill.

3.3 Results

A direct relationship in frequency and phase between the acceleration in the z-axis (up and down movement) and the solar module voltage was observed. We deduce that the cyclical trace at the solar cell (see Figure 9) is related to the striding motion of the subject. To test this hypothesis, we compare in Table 1 the speed of the treadmill with the subject speed. Additionally Table 1 shows the estimated speed from the accelerometer data. The speed is estimated from (step) frequency of the solar cell data and an estimated mean stride length. As can be seen, our hypothesis is supported especially at a treadmill speed of 1.39 m/s and below. At higher speeds (e.g. when the subject is running), both estimation methods incur large errors.

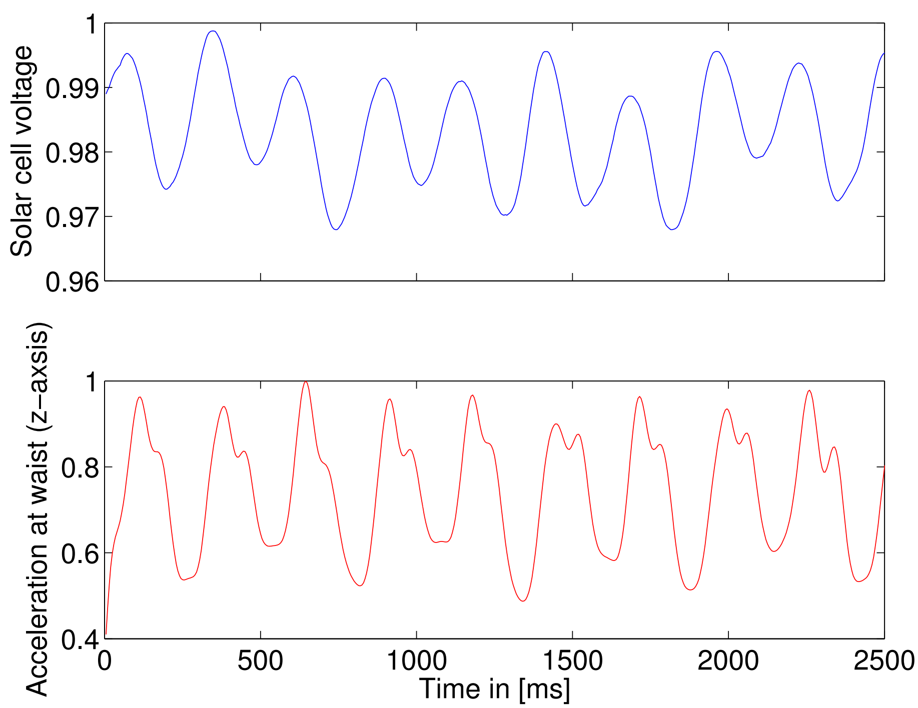

Fig. 9. Sample waveform of the normalised and mean filtered acceleration in z-axis and solar cell voltage at 1.39 m/s

Nominal speed from treadmill $[m/s]$	Mean stride length $[m]$	Est. mean speed solar cell $[m/s]$	Est. variance solar cell speed	Est. mean speed accelerometer $[m/s]$	Est. variance accelerometer
0.28	0.55	0.28	0.021	0.31	0.052
0.83	0.60	0.90	0.012	1.01	0.054
1.39	0.73	1.36	0.002	1.38	0.007
2.78	1.20	2.91	0.019	3.37	0.008

Table 1. Comparison of four treadmill speeds with sensor estimated speeds

Whilst the perpendicular sinusoidal model showed a resemblance to the solar cell measured trace (see Figure 10), it is not a conclusive match for reasons that we assume include that the model does not include rotational (forward and back motion and swing) of the shoulder. By fitting the model parameters speed is estimated to 1.69 m/s at a gait stride of 0.9 m and 0.53 s while the truth speed is 1.39 m/s (relative error: 22%). At the other speeds, the model error is greater than 30%.

4 Discussion

Indoor radiant intensity estimated with a solar module during a horizontal translation (straight trajectory) down a corridor shows little noise and resembles a sinusoid for the case examined here of regularly spaced light sources. It has been possible with a trained model approach to obtain an average error between model and measured data of 18 cm with a confidence of 83% over a trace of 7.4 m (see Figure 6). The centimetre scale 3D motion of the shoulder while walking has also been investigated. The effect of large scale horizontal translation was removed by performing the experiments on a treadmill. A comparison of acceleration and radiant intensity at the shoulder showed relatively good agreement. The validation of a model based on two perpendicular sinusoids has been initially investigated and showed some agreement for medium walking speed at 1.39m/s (see Figure 10). We anticipate a number of improvements with the modelling presented here. For example, we have not made use of the probabilistic algorithms or condensation algorithms more usually applied to such a problem when researching and developing context aware systems. Furthermore, a model based on rotations of a point on the shoulder in 3D space could also be considered.

We have begun to investigate how light data might be used to support navigational systems. The issues related to LuxTrace can be categorised into three main areas: the light sources, the environment and user related effects:

Light source issues include but are not limited to:

1. Light intensity measured at the solar cell reduces with increasing distance between the solar cell and light source(s). Intensity is also reduced if the plane of the solar cell is not perpendicular to the incident light.

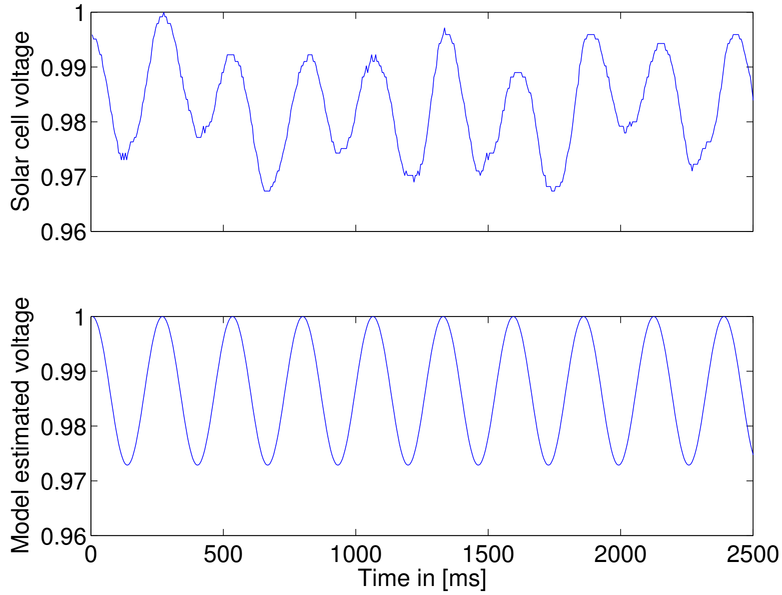

Fig. 10. Comparison of normalised solar cell measured trace at 1.39 m/s with the voltage estimated by the perpendicular sinusoid model, normalised data (model estimated speed is 1.69 m/s)

2. The way light sources are installed can also affect measured intensity. This can be related to the reflective and spectral properties of the objects around the light source such as a diffuser and reflector. Another aspect of light installation is encountered as the distance between two light sources is reduced, a light intensity maximum between two light sources can be created by superposition. For the trained model presented in Part 1, this maximum would be misinterpreted as a light source. Fortunately architects do not usually design lighting schemes based on such pronounced superposition for energy efficiency and visual comfort reasons. Exceptions might include areas where higher light level is required, e.g. work benches.
3. Light source intensity is related to the rated power (e.g. in the corridor tested lighting tubes are rated 35W whilst the adjoining offices are fitted with 58W tubes). Equally light manufacturers offer a wide range of colours of light (e.g. Cool White) that might form a basis for distinguishing electrical light sources based on their different spectra.
4. Ageing effects of fluorescent tubes usually go unnoticed by the human eye, although an intensity reduction of 20% can be expected in 2 years in an office environment.[4] Intensity decrease can be exacerbated by dirt on the tubes, so that a loss of 30% intensity in six months can be found in a garage for exam-

[4] Personal communication with a large Swiss light installation company

ple.[5] In the limit, all tubes will also fail, although in an office environment are usually replaced within days. The measurements made to develop the trained model in Part 1 showed that the few tubes tested had measurable ($\pm$ 5%) differences in intensity. However, we do not anticipate that these differences would form a basis for identifying tubes that could be scaled up e.g. from a corridor to a building.

5. By modification of fluorescent tube ballast, such lights have been used as a data broadcast channel. A number of scenarios can be found at [22]. Location tracking using fluorescent light sources might be simplified by having ballasts that allow each light to transmit a unique signature.
6. Because of the variable nature of daylight with respect to orientation, intensity and time of year for example, for our experiments we took a case that minimised the influence of daylight. We performed all tests at some meters from any window where daylight intensity is below electrical light intensity. Should we choose to examine cases that include daylight and fluorescent sources only, natural light might be distinguished as it would not have the characteristic variation (e.g. 100Hz in Europe).

Issues related to the environment include:

1. The influence of surroundings e.g. walls and objects. Their impact will depend on the distance to the objects from the light source(s), their shape and their reflectivity across the spectrum.
2. Availability of mapping information; it is understood that location systems that do not rely on such information being provided at the outset are generally preferred. Should map information be available, this information supports the tracking system by providing location constraints, e.g. impossible to walk through rigid objects such as walls.

User related influences include:

1. Each user has a different morphology affecting their height for example.
2. As the user moves, the position of the solar cells with respect to the body centre of mass will move e.g. due to user gait.
3. The head and or the body can block light paths, reducing the intensity measured at the solar cell.
4. For the case of solar cells on the shoulder, the orientation of solar cells with respect to the horizontal can be affected by looseness of clothing, gait, posture and the subject activity.

From our results with the human shoulder, we anticipate that limited applications near a light source that only require simple body motion data could be supported using solar cells as sensing devices. Such systems might be in context recognition, sports training (e.g. indoor golf swing trainer) or post-trauma physical rehabilitation. Given the lower cost of solar cells to other motion sensors, this presents an avenue for cheap rudimentary motion detection.

[5] Personal communication with a large Swiss light installation company

5 Conclusion and future work

Indoor radiant intensity estimated with a solar module during a horizontal translation (straight trajectory) down a corridor shows little noise and resembles a sinusoid for the case presented here. It has been possible with a trained model approach to obtain an average error between the model and the measured data of 18 cm with a confidence of 83% over a trace of 7.4 m (see Figure 6).

Centimetre scale 3D motion of the shoulder while walking has also been investigated. The effect of large scale horizontal translation was removed by performing the experiments on a treadmill. The remaining motion has been used, given step size, to estimate user speed (see Table 1). A number of influences and parameters that might affect using light sources to support location tracking have been mentioned in the discussion. These indicate many of the avenues that require further research. For example, the speed estimation approach from solar cells presented here should be verified with more test subjects, in positions other than directly below a light source and in more realistic trajectories. We anticipate a number of improvements with the models used here. For example, we have not made use of the probabilistic algorithms more usually applied to such a problem when researching and developing context aware systems. Furthermore, a model based on rotations of a point on the shoulder in 3D space could also be considered.

In order to improve the wearability of the concept, the use of flexible solar cells (e.g. from [23]) would better match garment specification than those used in the experiments presented. More generally, the results reported here support the feasibility of future sensor nodes that rely on the same device for both sensing and energy harvesting. Energy harvesting technologies other than solar (photovoltaic) could also be considered.

6 Acknowledgement

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