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Abstract

In this paper we consider the problems associated with placing optical devices on the human body. Whilst optical sensors and transmitters are already used by many researchers, the position of the device often appears to be chosen by intuition alone and without reporting any quantitative justification. We discuss simulating the user and device such that quantitative comparison can be made over a range of positions around the body for some of the main properties that dominate device placement — occlusion by the wearer, clear sight of the dominant workspace and amount of motion during user activity. Results are presented from our simulation and used to guide position selection in a rigourous manner. This performance-based design, together with the more social considerations which discount certain placements confirm the intuition of the many authors who have already placed their sensors.

1 Introduction

Visual sensors have attracted researchers in wearable computing since some of the earliest experiments [1, 2]. Such sensors have great flexibility to recover different properties from both the world and the user; namely 3D structure, object texture, user gestures, etc.

However, little or no research has been reported analyzing and comparing the behaviour of visual sensors in different body locations. The use of these sensors, and some others, is typified by non explicit analysis and placement mainly driven by researcher's intuition and experience. Current literature in wearable computing generally avoids design methodologies based on quantitative measurements; something that makes it hard to compare research results (a sole exception can be found in [3]).

In this paper we are interested in addressing the following questions:

- *Is it possible to* **quantitatively** *measure the parameters of visual sensors in wearable scenarios?*
- *Can these sensing parameters be combined to give a joint performance index?*
- *Can a design methodology be constructed for which the optimal placement is physically meaningful?*

We approach these questions using a 3D simulator based around a humanoid-shaped object. The results, while confirming previous assumptions in the literature also provide us with alternative placements. Additionally we gain tools that take us a step closer to automated design of sensor placement in wearable applications.

Before describing the simulations we first examine the sensor placements that are currently in use.

2 Wearable optical devices

Positioning an optical device on the human body is quite a problematic task, as occlusion, motion, social issues as well as criteria related to the purpose of the device must be taken into account.

For this paper we consider mainly cameras, although the discussion applies equally to any device for which the human body is opaque. In particular, field-of-view (FOV) considerations are important for any omnidirectional optical transmitter placed on the body, and any omnidirectional optical sensor.

Cameras used for wearable applications fall into two categories for this discussion; static narrow-view devices and omnidirectional devices. Omnidirectional devices include catadioptric, fish-eye and active systems where either the entire field-of-view is imaged at low resolution, or in the active case the high-resolution narrow-view sensor moved to any orientation. Narrow-view static cameras can only ever see a small part of the user or their environment, and placement is therefore entirely driven by the task. For wide-angle or omnidirectional sensors placement is less constrained and a range of positions are possible.

A variety of solutions appear in the literature. In [7, 8], hat-mounted cameras have been used to look down at the user's hands and reaching space, whereas in [9, 13] cameras are strapped to the wearer's hands themselves. In [10], a hat-mounted camera looks forward, an orientation also used when the camera is attached to a head mounted display [2]. In contrast, [11, 6] uses a camera worn on the chest, in [5] an omnidirectional camera is used above the head, and a wide-angle lens camera mounted at the back in [12] and in previous work [4] we placed a miniature active vision system on the shoulder.

In a previous paper [4], we identified three frames of reference for measurements that a wearable sensor makes:

I relative to the user body (e.g. sensing the manipulative space in front of the user's chest)

II relative to the static world (e.g. sensing the ceiling/floor texture to infer user's location)

III relative to an independent object (e.g. tracking an interesting object)

This task-oriented classification can help us to understand the criteria that should be considered. For working in the user frame alone all that is required is a stable view of the chosen area — often the handling space, and absolute field-of-view may be less important. For sensing the outside environment user occlusion is problematic and absolute field-of-view is more important. Both occlusion and user motion are problems when fixating resolution or processing on a particular part of the environment or independently moving object.

3 Simulating the wearable environment

Designing wearable computers is in general more challenging than their desktop companions because of one essential extra component: the wearer. This means that any design exercise must in the end be tested by humans, ideally outside a laboratory environment. For this and other reasons, researchers in the field usually perform user-testing themselves, adding further problems to the whole process of objectively comparing and sharing results[1].

An alternative is to use a system with (we hope) no inbuilt subjectivity. This suggests simulating both the person and the device and testing several conditions with the aims of both reducing re-design cycles and having a common ground on which to compare different options.

The utility of physics-based simulation in the modelling of humans has been shown by the field of Biomechanics. This research can teach us much about the short and long term performance of humans under different experimental conditions.

To simulate and compare positions for optical devices around a human body, we must first simulate the human form. The model we will use is a female example from the Human Animation Working Group [14], consisting of about 1000 markers (points) and 1800 polygons arranged into 16 body-segments which can be independently rotated to simulate any natural pose.

We have created software[2] to allow the simulated optical device to be positioned arbitrarily in space around the body, or for faster automatic tests placed a distance above any of the humanoid's polygons. Such positioning requires determination of the polygon's outward normal and centroid and positioning of the device a fixed distance along the normal based at the centroid (figure 1).

The utility of such a model is that the variables of position and distance above the body-surface can be varied automatically, allowing tests for a range of device heights over the whole body (which would be tedious at best on a real person).

Determination of occlusion in any direction can be made by emitting a ray from the chosen device centre and checking for intersection with any of the component polygons. Only polygons facing the camera need be considered, and refinements to further reduce the number of tests are widely reported in the ray-tracing literature. For visualization it is also useful to consider emitting rays from the device centre as equivalent to a central projection onto a unit sphere. This yields representations such as figure 1 (right), where the head is clearly visible to the right with the shoulder below it. The proportion of the sphere surface not occluded gives the absolute field-of-view.

4 Performance tests

We now present results from simulated measurements of field of view, viewability of the work-space and user-motion.

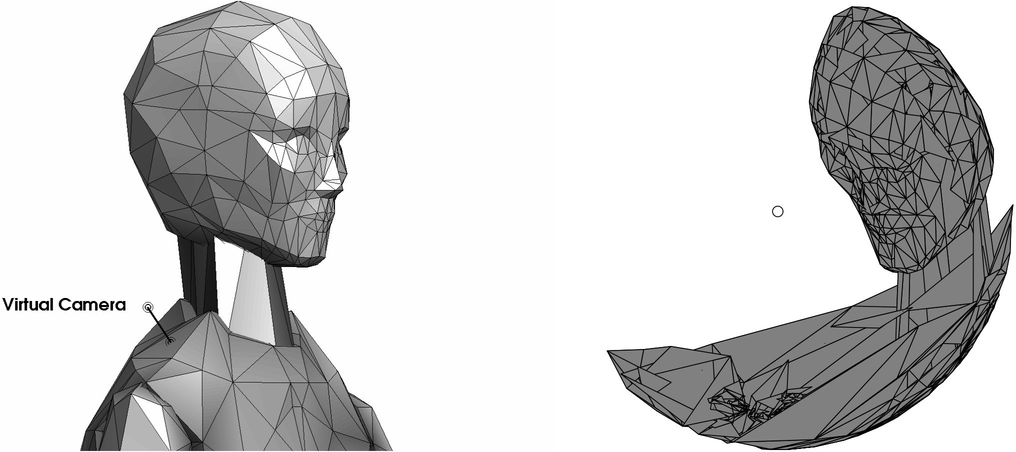
4.1 Absolute field of view

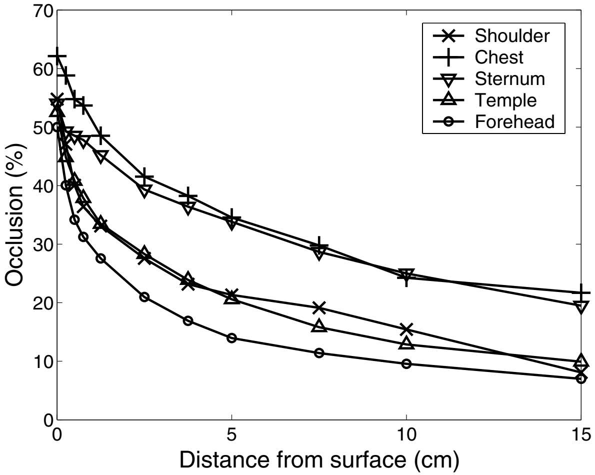
For the first of these tests, the camera is placed at distances of 12.5mm and 37.5mm above each polygon and the absolute field of view measured. This is done by casting rays in directions evenly spaced around the sphere[3] and measuring the ratio of those occluded to those not occluded.

[1] we include ourselves in the list of those who have "user-tested" their own systems

[2] Available on our homepage

[3] it is impossible to evenly space more than 20 points around a sphere because the icosahedron is the highest-order platonic solid, but repeated resection of the icosahedron's faces into near-equilateral triangles and projection onto the sphere-surface yields a very good approximation.


Virtual Camera



Shoulder
Chest
Sternum
Temple
Forehead
Occlusion (%)
Distance from surface (cm)
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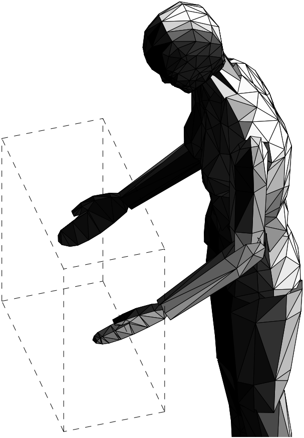
10
20
30
40
50
60
70
0
5
10
15



FOV and minimal motion are the primary requirements. We are also interested in maintaining a moderate view of the handling space, but consider it of less importance.

Figure 7 shows the results of combining the field-of-view, handling-view and motion results, giving an overall design score for each position. Gains were $g_{FOV} = 5$, $g_{handling} = 0.1$, $g_{motion} = 3$. As before favourable sites are shown dark and unfavourable ones light, suggesting that the best sites are on the head and shoulders.

This example is just one of several ways that the obtained data can be mined. An alternative is when candidate positions have already been determined satisfying some other design criteria. From the data, the candidates can be compared by calculating the gains that relate them. A further method is to use the data to warn of potential problems that might be encountered in a candidate position.

Alternative placements are important when, for example, we want to decouple the sensor's attention from the user's attention. This requires that the sensor is not placed on the head, and can be useful in a tele-cooperation environment when more than one person is embedded in the wearable-computer and more than one point of view is desirable.

In addition, careful sensor placement is essential when the wearable computer needs to take measurements of specific regions in the environment without user assistance. This is important when the user should not or can not be interrupted.

6 Conclusions

In this paper we have proposed a way to quantify the effect of sensor placement on the performance of a wearable visual sensor. The results consider field of view, region view and body motion, although other criteria might also be included (e.g. [15]).

The computed data can be combined to give an overall performance index weighted by design criteria. The peaks of this performance index match the locations used in current research, but with the advantage of showing possible alternative positions.

We have introduced the use of a simulation environment featuring humanoid-shaped objects for quantitative analysis in a wearable scenario. The results can be used to design a sensor that concentrates sensing elements on regions not occluded by the wearer. This is important in designing sensors which minimally fulfill requirements leading to higher resolutions, lower power and lower computing cost.

This simulation tool and methodology could be easily adapted for designing placement not only of conventional passive cameras, but sets of sensors worn in different body locations, omni-directional cameras, compound eyes, robotic sensors, laser pointers and general wearable optical-related devices requiring interaction with the world. Future enhancements could include more complex and varied human models and simulation of case situations including user pose and environment objects.

Acknowledgements

The virtual wearer was modified from an original VRML file by Cindy Ballreich ©3Name3D.

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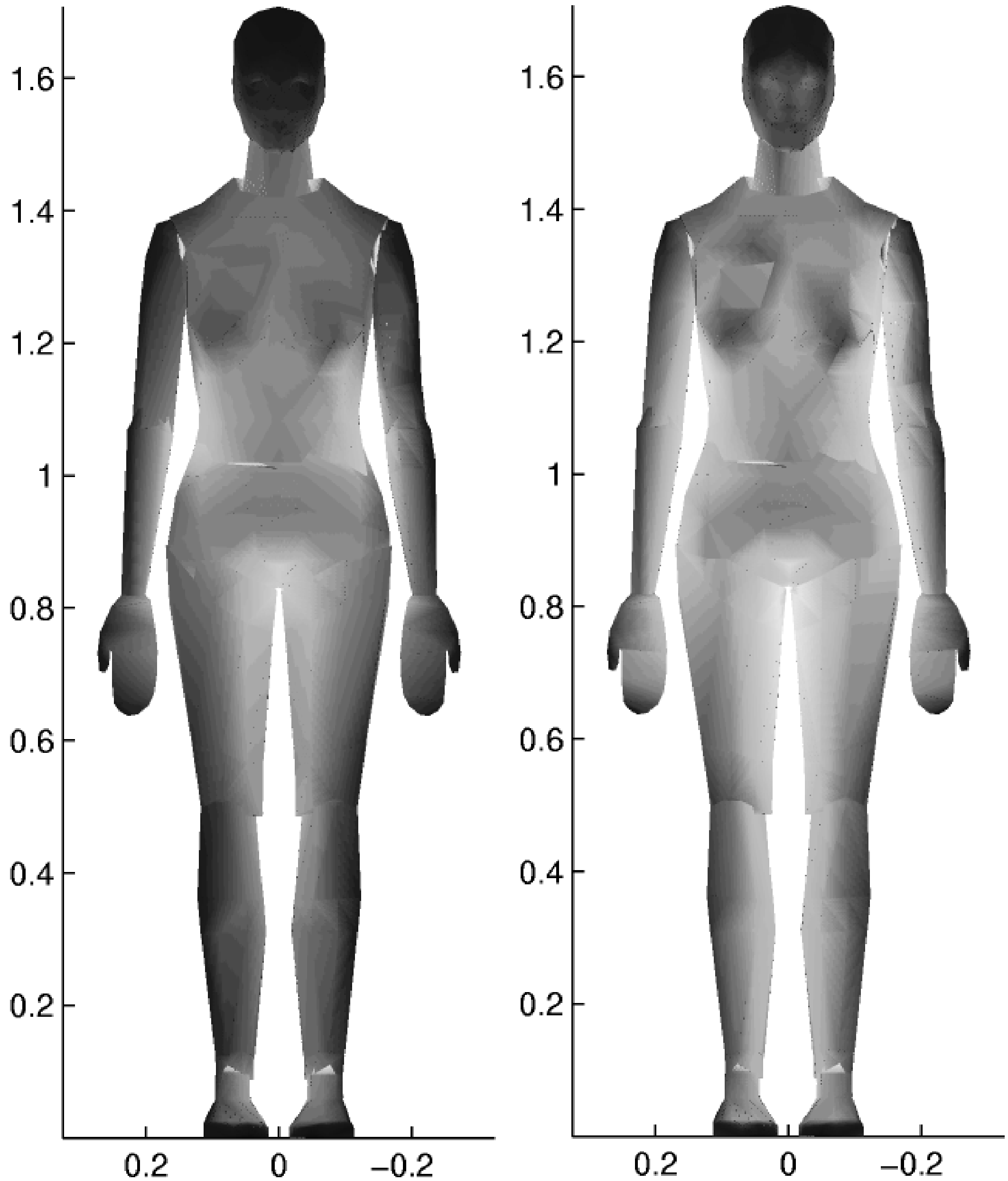
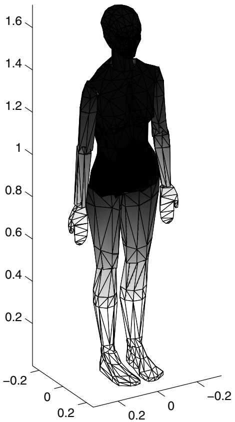


Figure 2. 3D map of the FOV of cameras placed all around the virtual body. Left: FOV Map generated by a camera placed at 37.5mm from every polygon in the body. Right: using a camera placed at 12.5mm. This latter one has fewer better areas since a darker colour indicates better FOV.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1.2
1
0.8
0.6
0.4
0.2
−0.2
0
0.2
0.2
0
−0.2