Handheld Devices for Mobile Augmented Reality

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ABSTRACT
In this paper, we report on four generations of display-sensor platforms for handheld augmented reality. The paper is organized as a compendium of requirements that guided the design and construction of each generation of the handheld platforms. The first generation, reported in [17]), was a result of various studies on ergonomics and human factors. Thereafter, each following iteration in the design-production process was guided by experiences and evaluations that resulted in new guidelines for future versions. We describe the evolution of hardware for handheld augmented reality, the requirements and guidelines that motivated its construction.

Categories and Subject Descriptors
1.3.6 [Computer Graphics]: Methodology and Techniques—Interaction Techniques

Keywords
Augmented Reality, mobile computing, 3D user interface

1. INTRODUCTION
Fueled by the increase of available mobile phone hardware and software, handheld Augmented Reality (AR) has become a paradigm for mobile AR applications. Thanks to their form factor, mobile phones come out as the preferred platform to bring mobile AR to the wide public. Nevertheless, the technically limited mobile phone hardware only provides a constrained platform for AR that does not necessarily match the requirements of all applications. In recent years, mobile AR has also become a test paradigm for industrial applications. These applications pose strict requirements on accuracy of the sensors that are used to generate the AR experience, namely tracking, video and graphics. Our work has focused on designing and producing a platform primarily for this breed of high quality AR applications. The hardware consists of a display device with external sensors and controllers. The development has been driven by qualitative evaluations consisting of experiences followed by interviews and surveys with experts in the public sector and industry. These interviews and observations provided requirements and guidelines for each generation of our hardware platform.

The analysis, design and evaluation of our platform in all its flavors has been part of three projects: Vidente and SMARTVidente focus on on-site modification and surveying geo-spatial data, whereas HYDROSYS aims at monitoring and management of environmental processes through interactive visualization of sensor data. Applications for these projects require accurate tracking, high quality graphics and video, and operate in potentially harsh environments: a robust platform is required that can hold all necessary sensors and controllers, and can cope with the external conditions. The novelty of this article lies in both the generation of robust, ergonomic devices for handheld outdoor AR, and the experiences gained and reported. Ergonomics and human factors are the foundation upon which all our research is constructed. We present a compendium of guidelines and best-practices, going from very experimental design for research purposes, to applications requiring to save weight and still provide the best AR experience in extreme outdoor environments. Thereby, we show how the functional requirements evolved from research in interaction with handheld AR standpoint towards more elaborate applications. In our application domain usage duration is longer than the generally “peek through the hole” actions supported by most current AR applications. Furthermore, to gain acceptance by end-users devices have to appear less “experimental” and be more robust to endure actual usage. The different stages of analysis and design of platforms reacted to four main categories of requirements that have a strong interplay:

Ergonomics: users should be able to hold the device ergonomically in longer interactive sessions

Robustness: the construction should protect in particular the sensors from possibly harsh weather and usage conditions

Compactness: the device-sensor combo has to be small, held comfortably and easily transportable

Modularity: the device should be reconfigurable based on user needs: sensors should be mounted or removed at will

At every stage we reflected the knowledge gained from the previous generations: hence, the fourth generation considers all categories of requirements and feedback we received over time. After a brief introduction on related fields of research, we will illustrate the foundations that provide requirements and boundaries for the design of handheld AR platforms. Thereafter, we proceed through all four generations of devices, showing how and what we learned throughout the iterations of requirement analysis, design and evaluation. We finalize this paper with a reflection on the experiences we gained, describing guidelines for other researchers and practitioners to design apt platforms.

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2. RELATED WORK
Wearable AR systems can be classified as a subfield of wearable computing [9]. It has been around for almost 20 years and makes use of mobile computers in different sizes. Two main directions can be identified: the head-worn display direction using backpack-mounted laptops [16] and the handhelds' direction. The first direction is slowly diminishing due to the pace miniaturization of hardware proceeds [16] [2]. This trend can be observed clearly by the rise of AR applications available on mobile phones. Supported by processing power and miniature camera, applications can make use of different kinds of vision-based methods for localization. Though portable, mobile phones are still inferior to custom-made platforms. More recently, platforms are appearing that use handheld projectors for augmented reality, but are not considered in this article [8]. A few AR platforms, including the predecessors we built upon [14] [13] [12], make use of ultra-mobile PCs (UMPCs). Most platforms did not focus on ergonomics, but rather on a straightforward way of binding sensors to the UMPC. The general approach of attaching sensors and actuators to a UMPC is a combination of a Perspex case and duct tape, which normally does not lead to a highly ergonomic construction. Some exceptions are the AR mask by Grassell et al [3] and the MARTI demonstrated by Stutzman and colleagues [15]. Other devices like the Xybernaut setups separate the processing unit from the display, lowering the weight to hold in the hands, though are hardly used anymore. To our knowledge, our setups are the most robust and ergonomic handheld platforms for high-quality outdoor AR produced till current date. Finally, this paper describes rapid prototyping of devices, with foundations on the design of 3D devices [1]. It also encompasses the reasoning on the usage of different materials for devices, which has similarities to the design of some haptic devices [7].

3. FOUNDATIONS OF HANDHELD AR
The analysis, design and evaluation of platforms for handheld AR is driven by three aspects: task domain, sensors and controllers needed, and ergonomics associated with operating the device. This section provides the background on all三个 aspects and thus the crux to all the design stages of the four generations of devices. Throughout this paper, we will predominantly focus on the interplay between sensors, controllers, and ergonomics.

3.1 Task
Before designing the first handheld platform, we performed a detailed functional analysis on handheld AR applications [17], to better understand the interaction space. The result anticipated several forms of interaction that are desirable under this paradigm. Handheld AR applications stem from many domains, varying from entertainment, to city navigation, and engineering. Many of these applications share features of mobile applications, in particular of location based services (LBS) [6]. Generally speaking, users perform navigation actions (viewport manipulation and maneuvering, including map interaction), simple system control actions such as visualization mode changes, straightforward object manipulation actions (often using a lens-metaphor), and only limited numerical input. It was found that in most applications interaction is clearly dominated by the viewing of data. When analyzing the functionality of these tasks, we noticed a high variety between accuracy, speed, frequency and duration of actions and no clear association between a task and a controller. The duration of interaction also varies widely, between less than a minute for simple tasks, up to about 30 minutes for complex, and possibly collaborative tasks. For a more detailed taxonomy of tasks, please refer to [17].

3.2 Sensors and Controllers
One of the main requirements in the mobile AR domain is a self-contained system holding all devices that are required for the application. The platform has to serve all requirements of these devices, such as power and connection.

AR requires several sensors to accurately register augmentations in 3D. For graphical augmentations in (handheld) AR, this implies that the pose of the camera capturing the real world must be known to calculate relative poses to render augmentations. Registration accuracy is determined by the quality of sensors and the implemented technique. Localization is generally achieved using GPS or a vision-based approach, depends on sensor fusion and methods such as differential GPS with correction signals [5]. An orientation sensor is often included to complete the pose estimation. Finally, live video is needed to generate AR for which, theoretically, any camera can be used. However, several camera characteristics affect perception of the AR experience. The field of view and focal length define the active viewing area. A reasonably high resolution that matches the screen aspect ratio is desirable, whereas high frame rate helps to generate a smooth experience. Allocation plays an important role both for sensors and controllers. All distances between the camera and sensors used for localization must be measured and calibrated for accurate localization. To simplify this procedure, the orientation sensor is mounted preferably below the camera. The GPS antenna should be mounted at a fixed location where signals are not blocked. Also, offsets to accurately specify location should be known, although for normal GPS with error larger than 1m this is not necessary.

Most handheld computers are equipped with a number of controllers. At a UMPC, control ranges from 2DOF to 6DOF, and make use of both isometric and isotonic control: handheld AR interaction is often bound to the platform at hand. Handheld computers generally include a micro-joystick, a couple of buttons possibly associated with a keyboard, or click switches. These controllers often do not afford fine-grained action and may be difficult to reach. Next to buttons and micro-joysticks, most platforms also include a touch screen nowadays that can be operated by finger (direct input or gestures) or a pen. Camera and orientation sensor can also be used for viewpoint interaction, though this is not very common due to the decoupling of visual and movement. Finally, in cold weather, the user might need to operate the device while wearing gloves, further restricting the choice of controllers.

3.3 Ergonomics
User acceptance of a handheld device can be ascribed to its ergonomics. Ergonomics is determined by several interrelated issues: pose, grip, controller allocation, weight and size. The pose is defined by the bio-mechanic system of the wrist, arm and shoulders and mainly states the angle at which the device is held. Regulated by the way the user has to look at the screen to view the world around, the pose may be at eye-height or lower, with varying distances from the body. The grip, the way the user holds the device with the hands, affects the comfort of holding the device, may limit fatigue, and can support simultaneously holding and interaction with the device. Users normally require a power grip, which avoids the device from slipping from the hand, which may occur especially in heavier setups. The ideal diameter of a grip is around 76mm (from fingertips to palm), at which it increases the strength of the wrist. Unfortunately, with smaller devices the size is hardly achievable [10]. Depending on the device weight and size, the user makes use of a single or two-handed grip. A two-handed grip is
Table 1: Dimensions of computers, sensors, controllers and associated cabling.

<table>
<thead>
<tr>
<th>Device</th>
<th>Size (W x L x H)</th>
<th>Weight</th>
<th>Length and Size (W x L x H) of bundle</th>
<th>Weight</th>
<th>Version</th>
</tr>
</thead>
<tbody>
<tr>
<td>Computer</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sony Vaio UX</td>
<td>130 x 100 x 38 mm</td>
<td>517 grams</td>
<td>N/A</td>
<td>N/A</td>
<td>1,2</td>
</tr>
<tr>
<td>Panasonic CF-U1</td>
<td>184 x 151 x 57 mm</td>
<td>1060 grams</td>
<td>N/A</td>
<td>N/A</td>
<td>2,3,4</td>
</tr>
<tr>
<td>Sensors</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inverse sense IC3</td>
<td>26 x 39 x 15 mm</td>
<td>17 grams</td>
<td>4.57 meter / 120 x 45 x 22 mm 120 grams</td>
<td>85 grams (incl. adapter)</td>
<td>1,2,3,4</td>
</tr>
<tr>
<td>Ublox GPS</td>
<td>39 x 46 x 12 mm</td>
<td>42 grams</td>
<td>5 meter / 110 x 40 x 22 mm 65 grams</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Uye Camera with lens</td>
<td>55 x 54 x 24 mm</td>
<td>70 grams</td>
<td>Short USB cable 8 grams</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard Webcam</td>
<td>62 x 30 x 21</td>
<td>30 grams</td>
<td>60 cm / 50 x 10 x 4mm 15 grams</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Standard USB Hub</td>
<td>58 x 35 x 15 mm</td>
<td>21 grams</td>
<td>Short USB cable 8 grams</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Battery pack (4 x AA)</td>
<td>54 x 54 x 15 mm</td>
<td>110 grams</td>
<td>N/A</td>
<td>N/A</td>
<td>2,3,4</td>
</tr>
<tr>
<td>Controllers</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RCube-X Multi wireless hub</td>
<td>61 x 22 x 14 mm</td>
<td>20 grams</td>
<td>N/A</td>
<td>N/A</td>
<td>1</td>
</tr>
<tr>
<td>Various midi actuators</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>Bodnar USB board</td>
<td>55 x 33 x 9 mm</td>
<td>10 grams</td>
<td>N/A</td>
<td>N/A</td>
<td>1,2</td>
</tr>
<tr>
<td>Genius Maxfire Pandora Pro</td>
<td>41 x 81 x 12 mm</td>
<td>27 grams</td>
<td>Short USB Cable 8 grams</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>

often required to avoid the tilting of a heavier device, or when the user needs to interact directly with the content on the screen (without using a pen). Balancing is frequently a result of fatigue caused by holding the device up: users may need to hold a device at eye height for several minutes, which may cause fatigue such as muscle tremble. Lowering the device by one foot can easily double the duration of holding up a device without experiencing fatigue [14]. Weight-balance strongly affects the ergonomics of a pose. When a setup is off-balance, in certain poses the tilting of a device will quickly result in fatigue, in particular when a non-ideal grip on the device needs to be maintained. The control allocation is in direct interplay with both pose and grip. The locations of the controllers in the device, and the relationship between location of controller and grip defines if a user can directly control an application, or needs to change the grip on the device. Whereas micro-joysticks are mostly placed at reachable locations, in particular touch screens require the user to grasp the device differently. Though almost obvious, ergonomics is highly affected by the weight and size of the different kinds of computers and sensors that are coupled in the handheld construction. The higher the weight, the more restricted the user may get. In Table 1, we provide an overview of the weight and approximate size of the various computers, sensors and associated cabling that are carried around.

3.4 Requirement summary

To summarize, we can make several statements that apply to the design of handheld platforms for high-quality AR. These requirements are tackled throughout the four generations of devices we present in Section 4. These requirements relate directly to ergonomics, robustness, compactness and modularity.

- Match sensors and controllers to the needs of the application
- Beware of the dependencies between sensors and place them correctly in relation to the display device
- Provide easily accessible and well performing controllers
- Integrate all devices without destroying ergonomics
- Support ergonomic poses and afford a good grip
- Keep weight and size limited, and balance the construction

The requirements are in direct relation to the display device (hence, screen and computer) being used: the device is the starting point for defining needs on sensors and controllers. It may come with sensors that could be used, such as a build-in camera or tilt sensor. However, in most cases these sensors have similar qualities as mobile phone sensors and need to be replaced by higher quality ones. It should have a bright and high-contrast screen for outdoor use, preferably with an anti-reflective surface. Furthermore, it should have low-power consumption to ensure long operation. Both the data received from the sensors and the actual graphics overlaid on top of the video will likely pose higher demands on processing power. As a result, most AR applications will benefit from a computer with a graphics processor. In the past, the Sony Vaio UX platform was the dominant display choice, but is not produced anymore. Meanwhile, new platforms have taken over including small tablets or robust UMPCs such as the Panasonic CF-U1.

4. HANDHELD DEVICE GENERATIONS

The motivation behind the iterative design cycles was the creation of a platform that affords mobile, high quality AR. Table 1 lists each piece of hardware we have used, its weight and dimensions, and dimensions for the cabling it requires. The table includes a column indicating what version(s) of the platform use each piece of hardware. The cabling is relevant for all but the first generation of our device, because this version relied on specially tailored electronics (USB hubs, and joysticks) and cabling to reduce space requirements. This section describes each generation of our platform, emphasizing its requirements, design and evaluations. In particular, we stress how the results of each evaluation influenced requirements for the next generation of the platform.

4.1 Vesp’R: ergonomics and experimentation

The particular motivation for the first generation was to open new possibilities for spatial interaction using handheld AR, as well as to experiment with ergonomics of one and two-handed interaction. We explored both conventional controls (joysticks and extra buttons) and non-conventional controls (bend sensor, grip camera) and set out to create a new experience for handheld AR. This generation has a strong focus on ergonomics and compactness, while modularity is only considered for controllers and interaction modality.
4.1 Requirements
The requirements for the first platform derived from evaluations on UMPCs, ad-hoc constructions [17], and from analysis on handheld AR. Adding to the requirements introduced in the previous section, the platform was aimed at studying pose and interaction possibilities: the platform had to allow both single-handed and two-handed interaction. It also needed to support multiple interaction methods, to enable experimentation with non-conventional controls and interaction modalities. The controls had to be allocated such that when interacting with the application in one pose, the user does not need to change pose to reach a certain control. After studying ergonomics on grip, it was decided that a power grip is needed to balance weight. Allocation of controls and sensors needs to be carefully planned with respect to the expected poses for interaction, so that weight balance is maintained without causing unnecessary strain in the arm lever-system biomechanics.

4.1.2 Design
We initiated the design process by going through a number of iterations of designing and evaluating mock-ups with a small user group. The mock-ups were used to evaluate different kinds of poses, grips and control allocations that lead to the general form of the platform. To comply with multi-modality of pose and interaction requirements, the platform was designed as central (base or "backpack") unit integrating the UMPC and all sensors. Controllers are placed on handles that connect to the base unit at specified locations. For two-handed usage of the construction, we placed two handles at the side of the base unit. The base unit was designed to hold most of the sensor packages in a box. A mount for the camera with room for an orientation sensor below was allocated externally, as well as the GPS antenna (mounted on a short pole at the side). All cables were measured to the smallest distance, and shortened such that each sensor would be connected without wasting space in spare cabling. A USB hub was modified to use on-board connectors to save space (from 4cm for normal USB to 5mm for on-board 5-pin connector). We experimented with general forms of grips, in which different kinds of controls could be embedded using plastic boxes, foam, clay and other materials for mock-ups. From these studies, we found out that the grip itself resembles that of similar devices like a drill or joystick; outside its scale to hold all electronics in a balanced way, the form is hard to improve. In the first handle, based on the controller allocation plan, we mounted two joysticks, usable by index finger and thumb respectively. The idea was to map constrained interaction techniques on both micro-joysticks to control specific axes in translational task with a dedicated controller (see Figure 2). We also included 3 thumb-operated buttons, and one that could be reached by either the index finger or the middle finger. All controls are mapped to a USB board from an off-the-shell joystick. The second handle is a test bed for alternative, unconventional MIDI controllers, and including quasi haptic input methods relying on touch sensitive Piezo sensors. Initial experimentation shows limitations in the usage of Piezo based elements: in single handed configuration, the force needed by the fingers to balance the construction prevent fine-grained control. Thus, only the secondary control unit includes a Piezo sensor accessible by the thumb, and a bend sensor that can be used by the index finger. The latter can be used well to control ranges of values. In addition, a wireless camera and laser pointer are mounted in the joystick for additional tracking and interaction purposes. The single-handed version requires to detach both handles from the sides, one handle can be mounted below; the second handle could be put away, or used for freehand (spatial) interaction. The handles were attached to the base unit with normal screws. Later we designed a handle specially for one handed interaction. Calculating the approximate weight of the case and peripherals against the weight of the UMPC, we placed the handles directly behind the back of the UMPC, close to the weight equilibrium. This supports a balanced grip on the device. In this version weight and size were quite optimized due to the alternative cabling of devices. This generation is produced using nylon-based STL with a wall-thickness of around 3mm. The model is covered with a thin velvety-like rubber and is partly glued, partly screwed.

4.1.3 Evaluations
We performed two formal evaluations to verify acceptance of the platform and the interaction modes it affords (for complete results see [17]). In the first evaluation, 17 people used the Vesp’R in single handed mode. Weight-balance and grip were rated acceptable, still people would rather use a lighter device. Controller placement was well received. Observations showed that people held the device in an unintended but obviously convenient manner by holding the base unit with the non-dominant hand to stabilize the device. The second evaluation compared the Vesp’R to constructions used in research and a barebone UMPC in terms of ergonomics, weight-balance and fatigue. The single-handed Vesp’R scored “acceptable” in weight-balance, indicating that the construction was...
This generation came as a first attempt to cope with requirements of robustness and weatherization. The two-handed Vesp’R scored significantly well in all tested conditions, indicating that the increased weight of the installation can be dealt with in an ergonomic way.

Discussion. Interaction with the single-handed version is possible, but not ideal. Both evaluations showed that holding the device single-handed is not very ergonomic for longer sessions. Leaving the second hand free for pen-input or real-life communication would require another approach, particularly for longer sessions. A positive whilst unintended effect of the base unit is the rather ergonomic pose it affords: the platform can be held from the base unit single-handedly as shown in Fig. 1. This pose is particularly comfortable when the elbow is placed against the waist, resulting in what we call the waist-pose. The two handed version advances ergonomics of handhelds significantly, in such a way that people perform comfortably even with double the weight of other devices. Proper controller allocation affords fine-grained actions even with the non-dominant hand. This version has been continuously in use since its construction by researchers and end-users. A main drawback of the first version is its structural unstability. The mechanism to attach handles weakens the construction, and it often had to be repaired and reinforced. Specially tailored electronics made it difficult for people to fix problems or extend the platform by themselves. Extending the platform with new sensors is possible insofar as these fit in the base unit, while new controllers require designing a handle.

4.2 Bulk’R: robustness and weatherization

This generation came as a first attempt to cope with requirements for a robust, all-weather device for outdoor use. The previous generation, developed for research was too much of a prototype. Its design, aimed at minimizing weight and dimensions of all parts led to specially tailored electronics that were difficult to replace. From the usability and human factors stance it was well received, and it drew enough attention that it was constantly in demos and presentations, going back to the lab only for repairs. However, the multi-configurability facet (two-handed, one-handed) and its specially tailored electronics made it too much of a prototype. Robustness was not among its requirements, and certainly not among its features. When the HYDROSYs consortium issued its request for an all-weather platform, it was viewed as an opportunity to create a robust platform for outdoor use. This platform was designed with two very different computers in mind, and initially covered the same external sensors as the previous one; although it has been extended to use more, even experimental, sensors (see Table 1).

4.2.1 Requirements

To meet the weather resistance requirements of outdoor use, the unit had to enclose and protect all sensors. Furthermore, the strict robustness requirements called for a specially tough body, and standard electronics that could be replaced by off-the-shelf components. A new requirement brought about after testing the old platform was the need for batteries to supply the external USB hubs and sensors. The Sony UMPC was tested with all devices and could only run up to 30 minutes when everything was connected and generating data. This limited its usability mainly to demo sessions. To extend the runtime expectation, external batteries had to be used to supply the USB hub(s) and all the external hardware. The Panasonic CF-U1 tested under the same conditions, has a battery life close to 4 hours. The requirements for interaction from the applications that used the Vesp’R proved more limited than initially evaluated, thus our functional evaluation had to be revisited to limit spatial interaction. Most of the non-conventional controllers were removed, adding 1D controllers and some buttons.

4.2.2 Design

The design was divided in a grip and a housing that holds sensors and the computer. A housing in the size of the Panasonic computer was designed to enclose the Sony computer to protect it from weather effects and sunlight. When using the Panasonic this housing is removed. The three parts are joined semi-permanently using a screw mechanism, only to be separated for exchanging the computer. The part designed to be removed is the top cover. This part has a fin that reaches to the bottom of the backpack. All the hardware is attached to the fin, and can be easily removed by removing the top cover. We exploited the findings on the pose, grip, and weight balance from the previous version: creating a new version of the grip that would improve robustness. From the previous version we knew that single-handed interaction can be ergonomically supported. This time, however, we needed to create a stable, robust single-handed grip. The grip part integrates single and two handed grips in a stable but massive construction. This grip allows the user to hold the device with one hand from below and operate the touch...
display or pen input single-handedly for short periods, or to operate it in two-handed mode using the build in controllers (a micro-joystick and two 1D-controllers). To change between single and two-handed operation modes the user has to regrasp the unit. This generation is produced using nylon-based STL, having a varying wall-thickness of between 3 and 4mm, with several solid parts (the grip). The model only holds few connections that are glued, and several nylon screws to connect the grip with the container holding the cables and devices. The top of this container can be screwed too with nylon screws.

4.2.3 Evaluations
This version was evaluated mainly through informal observations and interviews with at least 50 users. The unit was brought to numerous demonstrations of outdoor projects where specialists from industry and the public sector could test it. During these sessions, we noted down observations and critiques from people working in the fields we are concerned with. In general, the unit robustness was appreciated. Throughout all evaluations people were confident that the unit was stable and would not break or fall apart. However, it was often criticized by its sheer weight and bulkiness. With respect to controllers and their allocation, the interactive aspect of the unit was well received except by researchers, since the controllers are just the necessary ones and do not allow further extension. The controllers were found appropriate for prototype tasks that involved mainly browsing data, without having to control more than a couple of menus. From one of the associated projects we received a critique as to why we were including joysticks and advanced controllers, if only a bunch of buttons would do (to just switch on and off some view modes that is). However, the main critique we got from experts was that they cannot fit it in a backpack or bag and, of course, its sheer weight make it unusable after 10 to 15 minutes.

Discussion. The first thing people note about this generation is how bulky it is. Even after adding a belt, it was still considered heavy and not ideal to operate. The fact that the pack needs to enclose all sensors requires implies considerable space requirements. A subtle matter that might have gone unnoticed is that we strived to keep the customized electronics to a minimum in this version. Consequently, the new platform had to allocate not only bulky connectors (USB vs on-board 5 pin connectors), but also lengths of cabling. The IC3 from Intersense alone comes with a 5 meter long cable, plus a serial-to-USB converter that is bigger than the sensor itself. The cabling and electronics increased the space requirements even further. Weight balance was still appropriate, but the extra material needed for robustness added to the cables and electronics. The differences with the old version were pretty much noticeable. By the time the Panasonic computer was tested on this platform, it was already considered heavy and bulky. This UMPC only added more weight to the setup. Even if the computer could run for four hours on batteries with all the sensors connected and generating AR content, the added weight and bulkiness reduced the user experience to below the older unit (less than 15 minutes). Production-wise, the construction of the unit is better than for the previous version, but not at all a simple task. Some screw-connections also tend to break (the lid of the container). Finally, with respect to ergonomics, the waist-pose was increasingly used, which was no surprise when considering the weight of the robust yet heavy setup.

4.3 Ice’R: compactness, portability and assembly
After the second generation, we had to revisit several issues. Strict requirements from end-users impose that the unit be portable in an ergonomic manner, in the sense that the user must be able to move relatively larger distances carrying the unit, albeit not while using it. Further restrictions on size of devices required the new generation to be more compact, to be carried more comfortably and stashed away easier: simply said, the previous version was too bulky. Furthermore, the device should be easy to assemble by an end-user, and could benefit from better production methods, hence reducing production time.

4.3.1 Requirements
This generation of the handheld platform had to react to the portability and production requirements being made. Exchanging a sensor or accessing cables should be a simple task and the device should be easy to produce to cut production time. Simultaneously, the device should become smaller and more portable. The Panasonic CF-U1 replaced the Sony as the preferred platform in light of its robustness, weather resistance and long runtime expectation; all its most wanted requirements for outdoor applications. With the increasing importance of the waist-pose, we also had to reconsider ergonomic issues, in particular pose and grip. As noticed while evaluating the first and second generations, in longer duration sessions users are often forced to take the waist-pose. This pose implies a potentially dynamic angular offset between body and screen: the screen of a heavier device is held under different angles, to bal-
ance the weight and limit fatigue. This dynamic aspect affects the angle in which the camera has to point forward, which is generally fixed or difficult to change. At this stage of the design phase, finding a mechanism to dynamically angle the camera-orientation sensor combo was thought to be beneficial. With respect to compactness, the added weight of the computer and cables brought us back to a struggle with weight and space. Knowledge on grip and weight balance gained from the first platform was crucial to solve this problem: in particular weight-balance and tilt aspects were taken into regard when dealing with dynamic angular offsets.

4.3.2 Design
To match portability and assembly aspects, we had to refine in particular the outer form and all movable parts. As a starting point, we reconsidered the grips of the Vesp'R: however, this time we fixed the joystick-like grips to the body of the construction to avoid unwanted rotation of the handles. Furthermore, driven by the need to make the device more compact and easy to stash away, we avoided the usage of round and open forms: such forms take up too much space when stashing the device away. We ended up with a box-like form which is easily packable, yet still quite large. The platform was designed to be used in three alternative poses: strapped to the body with touch/pen input, held at arms length and closer to the eyes for shorter interaction sequences, or placed on top of a tripod. The first pose makes use of a strap around the back that keeps the unit in-place against the waist of the user, while leaving the hands free for operation or balancing the handheld construction. The second pose relies on the grips and a joystick input. To support the tripod mount, we embedded a tripod connector below the handheld platform. We envisioned that users would rely mostly on the waist-pose while surveying and only use eye-level pose for short periods at a time. This pattern of usage allows for longer sessions, because the arms can rest while in waist-pose. Furthermore, the tripod mount affords continuous usage and collaboration with others, since multiple users can look at the (small) screen, and no ergonomic conflicts are caused by weight. This generation applies a slider mechanism to put the parts together, simplifying production and reassembly, while still being weather resistant. A single panel at the back covers all the sensors and cabling that do not need to be accessed for normal operation. For the first time, we also focused on a robust yet flexible mechanism for the camera-orientation sensor combo. Both are mounted at the side of the computer with a lever mechanism to allow changing inclination of the camera-orientation sensor combo while using the device, or to stash it away for transport. Mounting the combo at the side of the computer greatly reduces space at the back, making the unit flat and rectangular. We also included a detachable antenna for the GPS unit. During transportation, the antenna takes too much space and thus increases the overall size and is a potential source for damage. Finally, to reduce problems with custom controllers (loose cables, size) we dismantled a small controller (a Genius Maxfire Pandora Pro) and placed it in a small box that could be slid into the left-grip of the device. The controller box holds several buttons and a mini joystick that can be reached well. This generation is produced using nylon-based STL with a wall-thickness of around 3mm. The model only needs to be glued on few places - most other parts are slid in. Magnets were used for opening and closing the lid on top of the camera-orientation sensor combo: the magnets do not disturb the orientation sensor when placed away far enough.

4.3.3 Evaluations
We performed a range of structured interviews with around 40 expert end-users. During the interviews we discovered that particularly those users that need to travel with light luggage found the device still to be too bulky. They suggested a modular platform: users wanted to put together their own display-sensor combination to save space by disconnecting unused devices, or exchange devices for smaller versions in less demanding applications. Experts were happy with accessing every part of the platform easily, but felt uncomfortable operating the unit. In particular the mobile part for the camera tilting resulted in undesired constant corrections.

Discussion. The flat form factor of this generation makes it easy to pack in a backpack, however, it is still very bulky. Although its form factor is not suitable for longer operation in grip mode, in the waist-pose and when alternating poses the operation can be extended to longer periods. Most handheld AR applications require the user to constantly make correlations between the real world and the view on the screen. This effect is accentuated when operating in waist-pose, because the user is facing down directly, while the camera is pointing forward: the user needs to look up and down frequently. Production-wise, this generation proved to be very successful - the limited glue connections and the sliders reduced production time to a few hours. Finally, we were not satisfied again with the controller box, which still caused too much trouble: the small size of the buttons often causes problems while pressing.

4.4 Cool'R: modularity
The goal for the last version was to devise the simplest construction possible, allowing a user to attach and remove sensors from the unit with ease: the construction should be as compact as possible. As such, a truly modular construction had to be found. Furthermore, weight restrictions made us consider different materials to reduce weight where possible.

4.4.1 Requirements
The main goal of the last handheld generation was to contrive a compact yet robust platform that could be dynamically modified based on users needs. Similar to previous handheld constructions, the setup had to be resistant to external influences such as weather, dirt, and object protrusion. Based on the comments on the third generation, we had to compress the size of the platform as much as possible. Users should be able to attach/detach various kinds of sensors: different tasks may require different sensors, including unforeseen ones such as a temperature measurement device. Furthermore, some users require the construction to be stripped down to the minimum: field workers are often constrained in what they can carry around, in particular when exploring remote sites. Hence, the construction had to be modular in such a way that leaving out a sensor would actually reduce the overall size: here, "modular" should be understood as a product of extensibility and compactness. Coming up with device that is both ergonomic and robust, yet also compact and modular is far more challenging than it may seem at first sight. As our experiences show, particularly compactness is hard to achieve, though very important to keep the device transportable and improve user acceptance. Furthermore, compactness should not minimize ergonomics.

4.4.2 Design
After analyzing different possibilities to mount external sensors and possible controllers in the previous devices, we decided to strip as much material as possible. We wanted to remove all parts that have a function that is performed by other or smaller parts to save weight. Analyzing the Panasonic computer, we decided to use the grip of the computer itself: it affords a good, close to power
grip due to the thickness of the device (diameter of around 76mm). Thus, we avoided the usage of external handles. Nevertheless, we also had to find a construction which could attach external sensors without blocking a part of the backside of the UMPC. We ended up with an X-like form (exoskeleton) mounted behind the UMPC, which leaves the hands free to grab the device from both sides. The exoskeleton also allows easier access to the hot swappable batteries of the UMPC, which was impracticable with the older versions that completely covered the back. Unfortunately, the exoskeleton has a reduced amount of material, rendering it vulnerable to structural damage due to the weight of modules attached to it. To strengthen the exoskeleton to withstand forces caused by weight, we combined it with an aluminium-enforced backbone. It gives the central part of the exoskeleton its stiffness against bending, and strength without uselessly increasing the weight. Bound by the pose a user tends to take when interacting with the device, the next stage was to define attachment points for the sensors. In particular the camera and the GPS antenna need to be mounted in a particular way: the camera needs to point forward, and blocking the tracking signals should be avoided. Users tend to hold the device in a 60-degree angle during operation: as such, reflections by ambient light can be avoided, and users can interact with the screen using an ergonomic wrist angle. To relieve the weight on the wrist we rely on a belt that connects diagonally to the UMPC, allowing direct access to the screen by the dominant hand. The belt also allows the user to rest the arms in the hip, "waist-pose", which has shown to be very beneficial in previous generations. We added a slider mechanism on the topside of the exoskeleton: the user can easily slide devices in and out that are needed for the task at hand. The variety of boxes we generated to protect the different camera-orientation sensor combos, and the GPS sensor all have a 30 degree angle; pointing forward when the user holds the device. This time, we also made a considerably smaller box for a webcam-orientation sensor combo that can be used when slightly lower camera footage quality is still acceptable. Unless the user makes use of a vision-only tracking solution to estimate pose, additional devices for tracking generate considerable bulk of cable that need to be stashed. In particular the camera and folded behind the UMPC, taking up relatively little space. The hull affords grabbing the device construction from the back single-handed, leaving the other hand available for other tasks. This pose was found ergonomic and useful in the first and second generations. Neoprene is extremely robust and weather-proof: it can hardly be ripped or punctuated, is waterproof, and absorbs shocks hence protects the devices inside. Due to its flexibility and stretchiness, we can actually compact the cables and additional devices by tightly folding the hull: the neoprene will compress everything to a limited amount of space without damaging the contents, which is impossible with any solid material we could have used. Hence, the neoprene "scales" well with additional devices by always compressing to the minimum space and size. Finally, we did not add any controllers to the unit this time: The UMPC has several buttons that can be reached well, and pen-input is possible using the grip and weight relieve by the belt. The main construction, the exoskeleton and the boxes were printed in nylon-based STL. Wall thickness is around 4mm for all structural parts, and 3mm for the boxes. The exoskeleton has a 2mm thick aluminium profile glued in for stability. The hull is made from 4.5mm thick neoprene.

Discussion. This generation has not been evaluated yet, though we can report on several initial observations. The combination of different materials in the device construction guarantees that the device is robust, compact, and easy to produce. The mix of materials considerably reduces the weight of the construction in comparison to the last two models that were designed for robustness (see Table 2). Enclosing each module in its own hull helps isolate and protect delicate hardware. However, we still need to evaluate the effects of the singular pose the device affords: users cannot look closer at the content on the screen while holding the device at eye height, since the camera would be facing up instead of forward.

5. LESSONS LEARNED
Throughout multiple phases of analysis, design and evaluation, we gathered experience on different aspects of improving handheld AR setups. In this section, we summarize the lessons learned, hoping that other researchers can benefit from the gained knowledge. The way the users hold the device, the grip, seems mostly associated with the primarily navigation-oriented task space. Even when performance of fine-grained actions is not needed, most users tend to hold the device in a power grip - there is not always a need for a precision grip to perform actions. We benefitted from the particularly thicker Panasonic UMPC to apply a power grip on the device itself:

Figure 4: Cool’R: complete device, modular boxes, lens protection and open neoprene hull, single-handed pose with pen operation.
the thickness and robustness of the device nicely affords a power grip, whereas the smaller and less robust Sony UMPC proved too small and fumble. The robustness of the Panasonic thereby reduced the necessity for an external grip (handle), and provided a solid backbone for mounting the additional construction that holds the sensors. Thus, the bigger and heavier Panasonics saved us some weight and size at the end, while still affording a good grip.

**Lessons learned:** Provide a power grip to hold the construction. Reuse, if possible, the device grip to save weight and size of the total construction.

A secondary grip to hold the device single-handedly appeared in the first two generations. Though some users make use of the single-handed grip to hold the construction continuously, it is used mainly to stabilize: the non-dominant hand stabilizes the device for the dominant hand to perform actions. This kind of behaviour was originally studied by Guiard [4], and applies to two-handed interaction in general. The secondary grip relates directly to the dominant pose the users seem to take: to avoid hand trembling and fatigue caused by the weight of the platform, users tend to hold the device at an angle at waist-height. Hereby, users tend to rest their elbows in the sides against their hips, resulting in what we call the "waist-pose". To further improve this pose, from the second generation on we introduced the usage of a diagonal belt that distributes the weight to the shoulders and back: in particular with pen-input, the stabilizing pose combined with the belt proved useful. Moving the device closer to the eyes and at eye height seems to be performed infrequently by most users, and may be associated with the small size of the screen: during navigation, explorative actions do not require much detail on the screen. Once a particular asset is noticed, the users may change under effect of reflections, which are still a significant problem. For the first iterations of this mechanism were unsuccessful (either too unstable or too cumbersome to operate). Modularity at the level of attaching a module for each sensor was impossible under such circumstances, and only after experimenting with a sliding mechanism in Ice’R we could start thinking about modularity as a possibility. Once a robust mechanism is available, the sensors can be grouped in functional units to create modules, or each of them can be considered a different module. The last generation of our platform uses a sliding attach/detach mechanism and STL boxes for modules. By using removable boxes for sensors, potential transportation problems caused by parts that stick out can be avoided, increasing robustness when not in use.

**Lessons learned:** Support the use of the waist-pose in combination with a belt, and rotate the sensors adequately.

Not surprisingly, the pose is often also dictated by the allocation and usage of controls. In particular with pen-input, the grip and pose on the handheld construction needs to be changed considerably. Similarly, with badly located controllers, users will need to angle their wrists in unnatural angles [17]. The number and allocation of controls is highly dependant on the kind and frequency of tasks. For explorative tasks (navigation), a simple control structure is often adequate. Similarly, for short task sessions, users can cope often with badly located or general-purpose controllers like micro-joysticks or buttons. Once applications become more complex, controls or interaction techniques should match the control structure: when touch screens are available, they can often match the complexity by providing adequate menus. In relation to the power grip, we can often refer to game joysticks, which generally have a good grip and ergonomic allocation of controls. However, care should be taken when building in controls: they are not only difficult to build-in in a compact manner, but also the electronics and cabling have to be planned thoroughly to reduce changes of malfunctioning. Specially tailored electronics require assembly time and can not be done by non-experts.

**Lessons learned:** Carefully plan controller allocation to reduce fatigue and pose changes. Use off-the-shelf controllers when available to simplify assembly.

Size is in direct relation to weight: the smaller setups we created were obviously lighter than the bigger ones. Nowadays, an influential factor on size acceptance is the mindset of end-users that is often influenced by mobile phones. Not necessarily understanding the technical foundations and differences between mobile phones and UMPCs, it is often difficult to explain without showing end-users the effects of a larger and better screen, more processing power and better sensors: the required quality of sensors and screen size often becomes evident when end-users use the platforms for a longer time. Notwithstanding, mobile phones and UMPCs are two different platforms. An alternative that proved most beneficial was to strive for full modularity. Attaching and removing sensors with their encapsulation saves space and weight once it can be achieved in a robust enough way: till now, our latest platform generation has proven well. The reader might wonder why modularity came in last in our list of requirements, only after a few iterations. The fact is that for the first generations, the set of sensors used for AR was pretty much fixed by project requirements. These sensors had been tested and provided the best performance at that time, thus we designed the first prototypes mainly for them, leaving extra space for device controllers that were planned before hand. Modularity often comes at the cost of robustness. Even though from the first version we used mechanisms to attach parts (e.g. the handles on Vesp’R), the first iterations of this mechanism were unsuccessful (either too unstable or too cumbersome to operate). Modularity at the level of attaching a module for each sensor was impossible under such circumstances, and only after experimenting with a sliding mechanism in Ice’R we could start thinking about modularity as a possibility. Once a robust mechanism is available, the sensors can be grouped in functional units to create modules, or each of them can be considered a different module. The last generation of our platform uses a sliding attach/detach mechanism and STL boxes for modules. By using removable boxes for sensors, potential transportation problems caused by parts that stick out can be avoided, increasing robustness when not in use.

**Lessons learned:** When striving for modularity, first experiment with the mechanism to attach/detach modules until it proves to be robust. Subsequently, create modules out of functional units and plan their allocation with respect to weight balance.

Robustness often correlates with weight: the more robust the construction is, the higher the weight, especially when complex production and assembly methods such as molds cannot be used. Stereo lithography (STL) is a useful method to rapidly create constructions that are not necessarily too heavy, when larger solid parts can be avoided. Nylon-based STL weights about 0.9 gr per cm3, hence, larger constructions can be made within weight boundaries: we used between 273.35 and 1235.1 cm3 for our constructions (see Table 2). Nonetheless, combining STL with other kinds of material is advisable: aluminum is light and can make the construction considerably stronger when used as aluminum-nylon composite, hence avoiding potentially far thicker STL models. Neoprene, on the other hand, is an excellent choice for robust and flexible "containers", compressing the contained parts. Not to be forgotten is the effect of the battery life of different platforms on weight: the Panasonic comes with two hot swappable batteries that have a long
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8. REFERENCES