Modeling Human Interaction Resources to Support the Design of Wearable Multimodal Systems

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ABSTRACT

Designing wearable application interfaces that integrate well into real-world processes like aircraft maintenance or medical examinations is challenging. One of the main success criteria is how well the multimodal interaction with the computer system fits an already existing real-world task. Therefore, the interface design needs to take the real-world task flow into account from the beginning.

We propose a model of interaction devices and human interaction capabilities that helps evaluate how well different interaction devices/techniques integrate with specific real-world scenarios. The model was developed based on a survey of wearable interaction research literature. Combining this model with descriptions of observed real-world tasks, possible conflicts between task performance and device requirements can be visualized helping the interface designer to find a suitable solution.

Categories and Subject Descriptors: H.1.2 User/Machine Systems: Human Factors H.5.2 User Interfaces: Input devices and strategies

General Terms: Design, Human Factors

Keywords: wearable computing, interaction devices, multimodal interaction, interaction resource model

1. INTRODUCTION

Wearable computing scenarios demand multimodal applications using a variety of interaction styles and devices in parallel. Take for example an endoscopy examination in a hospital. Doctors would like to access patient records during the examination. However they are handling the endoscope with their hands while talking to patient and nurse in turns. Interaction that needs to take place in parallel to these real world tasks clearly requires non-standard modalities. Probably even a combination of multiple modalities to be efficient.

Because workers in wearable computing scenarios have to deal with the real world as their primary task, their interaction capabilities are limited. Also, as the task progresses, the available modalities can change as well. The challenge lies in identifying the right modalities for the right situations, and in finding devices implementing interaction with these modalities, such that the computer interaction has minimal impact on the primary task's performance.

The selection of both, modalities and devices, requires in-depth knowledge about the primary task and which resources of the user are available at any given time. Normally, such information is gathered during field studies where user's are shadowed and observed. On that basis, designers compare what they have seen with interaction methods they know and build one or more prototypes. These prototypes are taken back to the user and tested. Usually, there are several iterations of prototypes until a satisfying solution can be found.

This process has two problems. First, if the designer is not also a domain expert in the target domain, there will be many unnecessary prototype iterations because of incompatibilities between the primary task and the chosen modalities/devices. As the whole context of use is new to the designer, the amount of new information can be overwhelming and even seemingly trivial incompatibilities can be overlooked. For example, in one of the authors' projects a headset was proposed for voice interaction in a medical ward round scenario. Later during mock-up tests with doctors, some of the doctors tried to use their stethoscope, which was incompatible with the simultaneous use of the headset.

Second, the design space for wearable computing applications is enormous. There is a large number of different interaction devices. Most of these devices can be used in several ways and can be worn in multiple places. Without help it is almost impossible for a designer to consider the whole design space and s/he will be limited to the devices s/he knows well.

This paper presents a method and tools based on a model of human interaction capabilities and interaction devices to improve this process in two ways. It provides a structured approach to gathering the right information during observations and analyzing this data using a library of interaction devices to determine candidate devices for designs according to the different situations during a primary task. Both goals are achieved using a model of human interaction resources that has been derived from a sample set of wearable

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interaction devices found in research literature. Using this model as a basis, more focused observations are possible. Furthermore, observed task traces can be used to simulate the availability of human interaction resources during the observed scenarios. At the same time, all interaction devices known by the software, instead of the designer, can be checked for compatibility, reducing the number of prototype generations necessary due to overlooked compatibility problems.

The remainder of this paper is structured as follows: first, a brief overview of related work is given. Next, the underlying interaction model of the approach will be presented. Section 4 uses an example to explain how the model can be leveraged in the design process. Finally, the paper concludes with a summary and future research directions.

2. RELATED WORK

Most research in the area of modeling interaction has focused on describing the device to computer interface as described in section 3.5. Some of these works have begun investigating the device to human interface by integrating human motions into the process of selecting appropriate interaction devices for specific tasks on a desktop computer. Toto by Bleser et al. [2] is such an example. However, they are not concerned with how many user resources are actually consumed by the interaction or how well the interaction integrates with a real world task.

Integration with a real world task has been tackled by Bürgy [4]. He describes a constraint model containing information about the user's task, its environment, application, available devices and the user. However the constraints are coarse and only few specific interaction devices are supported. Work situations are modeled on a high level with low granularity and do not consider changing requirements within any such situation.

There are some works that have been concerned with how wearable interaction devices influence the user. Notable are the wearability study of Gemperle et al. [10] and similar work by Dunne et al. [8]. Both papers focus on the wearability aspect leaving out influences of interaction and primary task.

How users multitask when using a mobile system while doing something in the real world has been investigated by Jameson et al. [12]. But their evaluation has been conducted post-design whereas the method presented here allows a limited analysis before a prototype needs to be built.

3. INTERACTION MODEL

The biggest challenge constructing a model of human-device interaction is finding the right level of granularity. If the model is too coarse, important aspects are missed and the model becomes useless in all but the trivial cases. However, if the model is too complex, the benefit of using the model is outweighed by the efforts invested into modeling. To achieve the right level of granularity, we examined existing wearable interaction devices in conjunction with likely wearable computing scenarios. In an iterative approach, we added and refined model concepts until the devices and scenarios could be represented by the model. This approach ensures, that the model is expressive enough for the devices used to construct it, but does not have any unnecessary complexity needed to model every interaction device imaginable. Therefore, it cannot guarantee, that future devices will fit into the model without modifications. However, the goal of a typical designer is to select appropriate interaction devices for multimodal interaction from a set of existing choices. Building radically different interaction devices is mostly the domain of researchers.

The set of wearable interaction devices used to construct the model was selected from research papers published at the CHI, ISWC and MobileHCI conferences. The following devices were studied: lightglove [11], Twiddler [20], FreeDigiter [16], gesture pendant [21], finger-ring [9], body mounted touchpad [22], acceleration sensing glove [18], GestureWrist [19], textile buttons [25], magnetic switch [17], vibrotactile display [24] and a forearm mounted keyboard [23]. The set covers a broad range of the concepts that have been used for human computer interaction.

The scenarios used to iteratively evaluate the model were an endoscopy and a ward round scenario in a hospital, a car manufacturing scenario and an aircraft maintenance scenario. These scenarios have been developed as part of a research project. Although all four scenarios were evaluated, this paper uses only the endoscopy scenario as an example.

3.1 Model Overview

The model describing interactions between the user, devices and tasks consists of four parts: a *human resource model*, a *resource consumption model*, a *device model* and a *task model*. The human resources model describes the resources a human can utilize for interaction with a computer system. Based on these resources, a resource consumption model describes how these resources can be affected by wearable interaction devices and user tasks. The device model utilizes the resource consumption model to describe a specific device's effects on the user and adds information about its interaction capabilities. The task model is similar to the device model, but captures the effects a specific observed user task has on the resources available for interaction. Figure 2 shows how the four models interact.

3.2 Human Resources Model

We identified three classes of resources the human body offers: actuators, sensors and body areas. Actuators are all means the human body has for influencing its environment, sensors are used for perceiving information and body space is used to attach devices and wear clothing. Figure 1 shows how the human body is divided into areas and how the three resource classes are distributed.

3.2.1 Body Real Estate

Wearable interaction devices need to be worn by the user. However, the human body offers limited space to attach them to. Gemperle et al. [10] have identified places on the human body where devices can be attached without interfering with natural human movements and where they are perceived as part of the body and not as separate entities. The areas identified were used as a basis but had to be extended in order to include all the devices surveyed. Extensions were necessary because Gemperle focused on placing PDA sized objects on the human body, whereas many devices used for interaction are much smaller. The smaller size offers additional places to put them without disturbing the user. A standard Bluetooth headset, for example, is easily attached to an ear fulfilling the wearability guidelines suggested by Gemperle. Other devices like the gesture

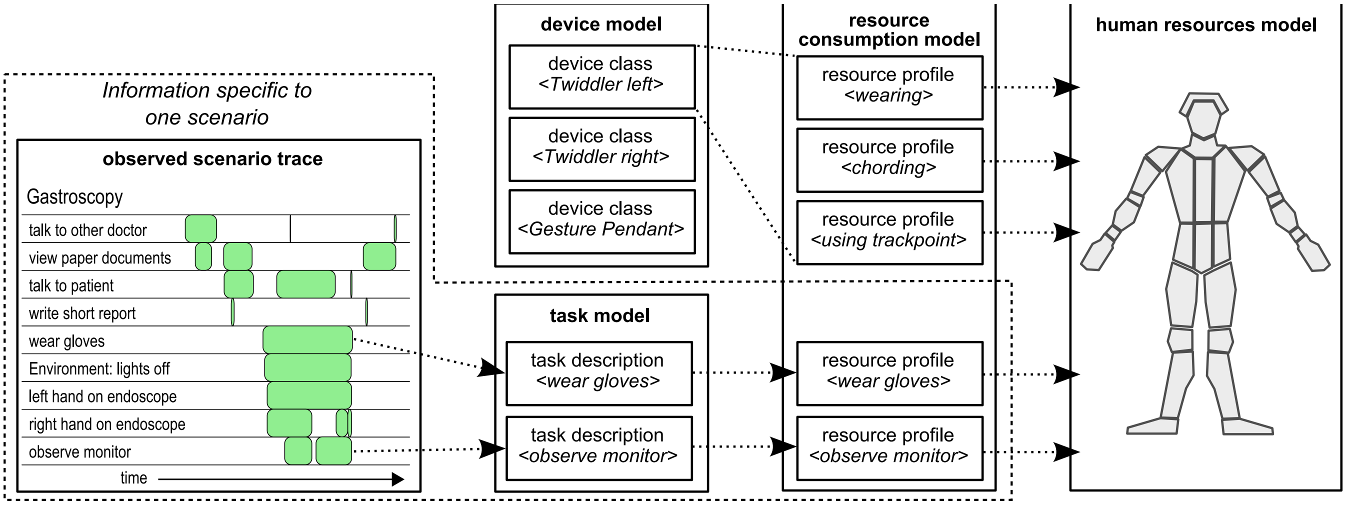

Figure 2: Traces of observed situations are associated with resource profiles for each task. Together with the human resources model the available resources at every point in time can be simulated. Device models are then used to compute when devices can be worn and used.

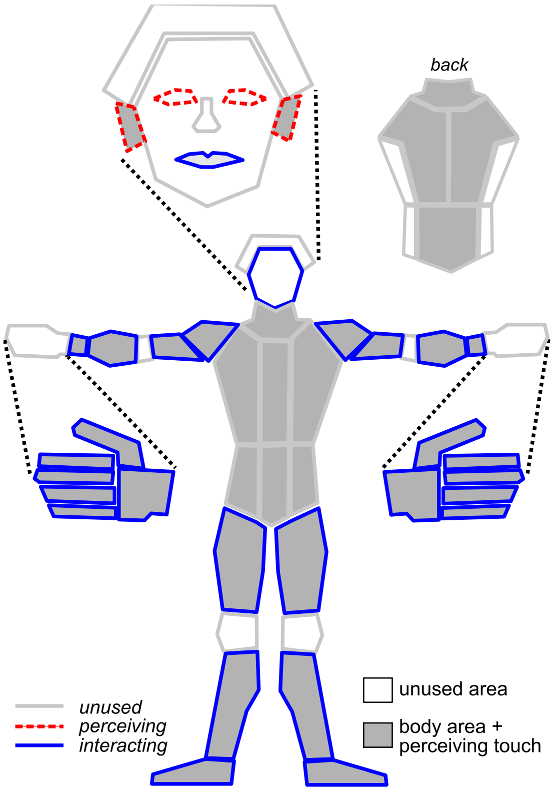

Figure 1: This figure shows the areas considered for interacting (arms, legs and head for movement; the mouth for speaking) surrounded by blue continuous lines. Perceiving areas (the eyes and ears) are surrounded by broken red lines. All grey body areas are used to attach devices and for perceiving touch.

pendant [21], that sits on the center of the torso suspended from a strap around the neck, do not fulfill all the guidelines but have been successfully tested in user trials. Therefore, additional areas have been defined to accommodate these devices (see Figure 1).

3.2.2 *Interacting*

The human body contains about 650 muscles that can be used in endless combinations to interact with the environment but only a few can be used in meaningful ways when interacting with a computer. Most of the interaction devices use movements of the arms, hands and fingers as their main source of input. This is because our hands are the most versatile manual tools we have at our disposal and also the most frequently used. Therefore, the arms, hands and fingers are modeled in more detail than the rest of the body. The Twiddler [20] for example uses the fingers for the chording function and the thumb for its TrackPoint, forcing separate areas for thumb and other fingers in the model. Other body parts that have been used successfully for interaction tasks are the legs and the head. Head interface examples are positional audio that reacts to the head's rotation and interfaces that detect nodding to confirm selections. Foot switches are frequently used in live music performances. The second major means of interacting with the environment is speech, represented by the mouth in Figure 1.

3.2.3 *Perceiving*

The human body has at least five main senses to perceive outside stimuli (sight, hearing, taste, smell and touch). Of these senses, only three have been successfully used in human computer interaction. Audio and video are the most common ways of presenting information to a user. Touch has been used for silent vibration modes in mobile phones, but is not as common as the other two. Smelling and tasting output devices have been investigated, but no practical applications have been found that are interesting in an interaction context because it is impossible to rapidly change what is perceived. Apart from the basic senses there are additional senses like thermoreception or the sense of balance but so far these cannot be used for interaction. Therefore, only sight, hearing and touch are integrated into the model.

Sight is modeled as a single resource. A human can only pay attention to one visual source of information at a time efficiently. Although visual signals can be used to catch the user's attention, they cannot be used to present complex information. This model is only concerned with the case of information presentation, and therefore only grants access to the visual resource to one task at a time.

Hearing is similar to sight, as several things can be heard simultaneously, but only one source can be used to present complex information at a time. Therefore, the hearing sense is also modeled as an exclusive resource.

The touch sense is different to the other two senses as it does not use a single small organ to perceive information. The whole human skin is covered with pressure receptors, theoretically offering the whole body to perceive information. However, a device triggering these receptors also needs to be in contact with that body part. Therefore, each body area in the model is a possible candidate for tactile information display and is modeled as a single resource. The authors are not aware of any study on the amount of information that can be perceived simultaneously via touch. Therefore, there is currently no limit in the amount of body areas that can be used at the same time. When research in this area becomes available this behavior needs to be changed according to the results. Until then designers have to be careful when combining devices relying on touch.

3.3 Resource Consumption Model

As the human resource model describes which resources are available for interaction, the resource consumption model defines how tasks and devices interact with these resources. There are three different types of resource consumptions, wearing objects, activities and more general requirements. Wearing objects is a model of how clothes and devices are worn and influence each other. Activities require either interaction or perceptual resources in different ways. Requirements enforce relationships between resources and their use that cannot be modeled with the other two types. Together, these three components form a *resource consumption profile* (short: *resource profile*). Examples are shown in Figure 4.

3.3.1 Wearing Objects

As wearable devices are directly attached to the user's body, the interactions between clothing, the device and the human body need to be taken into account. We wear clothes in layers and devices we wear are just another layer added (e.g. wristwatch beneath a sweater). These layers can be thought of as a stack of clothing and devices, starting with the user's skin. Whenever some piece of clothing or device is put on, another element is added to the stack (see Figure 3). As the body areas defined earlier are just large enough to hold a single device, they offer the right level of granularity for wearability, because conflicts are easily detected when each area can hold exactly one device. Each body area has its own stack and is independent of the other areas. Modeling the clothing layers as a stack also dictates how things can be added and removed from that body area, as elements can only be added to or removed from the top of the stack.

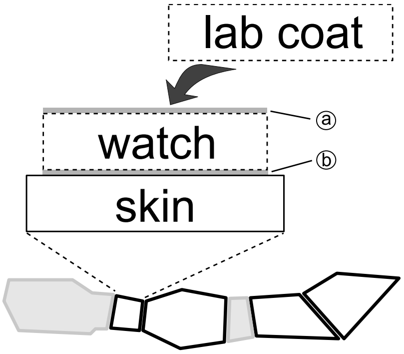

Figure 3: Stack of clothing on the wrist. A watch is already worn when putting on a lab coat. Reference points for requirements on the watch (a) *mustNotBeCovered* and (b) *requiresSkinContact*.

3.3.2 Activities

Activities directly use the interaction and perception resources available. Accordingly there is one operator for each resource type: *moving* and *speaking* for the interaction resources; *looking at*, *hearing* and *sensing touch* for the perception resources. As speaking and hearing are modeled as a single resource each that can only be used once at a time, the associated activity does not require any parameters, an activity or device either uses that resource or it doesn't. Sensing touch requires one additional parameter to know which body area is expected to sense touch.

Moving and looking at things are more complex activities. They require physical movement that depends on additional information. Movement of a body part can be relative to its current position, when using acceleration sensors, or relative to an object like pressing a button. Objects can be other body parts, devices on the body or external objects. However, depending on the target of the movement, other body parts might be influenced as well. When moving a finger to press a button on a headset, the whole arm needs to be moved to reach the target. However, if the same finger needs to press a button on a Twiddler worn on the same hand, no movement of the arm is necessary, as the device moves with the fingers. Likewise, looking at an object might require movement of the head to complete the action. These kinds of restrictions are inferred from the movement's target. The simulation environment contains appropriate logic to handle these cases correctly. Furthermore, whether a movement includes touching a target or not is an important factor. Especially in health care scenarios, hygienic restrictions prevent touching anything except the patient and specially disinfected devices.

Looking at things implies a target to look at. In most cases additional movement of the head is necessary, when the user is required to look at some part of his body or an external device. But a head mounted display for example moves with the head and requires no additional head movement when looking at it. At the same time, looking at a specific object also limits head movement. Imagine a doctor looking at a monitor for visual feedback of his endoscopy examination being required to turn his head for command selection.

3.3.3 Requirements

The third method of controlling how devices can be related to tasks are requirements. These are restrictions that are specific to a device or task, but can neither be described by an activity nor by wearing an object. Three of these requirements were necessary to describe devices and tasks used to derive this model. More might become necessary in other situations or with other devices. However, requirements are easily added to the model.

GestureWrist and GesturePad [19] are interaction devices that require direct access to the skin to measure changes in capacitance. Latex gloves worn during an endoscopy examination also need to be worn directly on the skin. The associated requirement *requiresSkinAccess* has a single parameter of an object it refers to. The watch in Figure 3 fulfills the requirement as its position on the stack is next to the skin.

Other devices require to be at the top of the clothing stack. The gesture pendant for example cannot perform any gesture recognition if its camera is covered by another piece of clothing. The requirement is called *mustNotBeCovered* and takes the object as an extra parameter. If the watch in Figure 3 had this requirement, the lab coat could not be worn over the watch.

Another requirement, *mustNotTouch*, is based on the endoscopy scenario. Hygienic regulations during an endoscopy examination require that the doctor must not touch anything with his hands that is not specially disinfected. That includes anything the doctor wears, but excludes devices used in the examination like the endoscope or syringes. This requirement takes a list exceptions to specify the objects this body part is still allowed to touch.

3.4 Task Model

The task model describes two things. First, it describes the resource demands of the different tasks a user has to perform in a given situation. Second, it provides example sequences of these task as seen by an observer [13] for an example see Figure 2. Together, these two are used to simulate the available resources over time for these example situations. Each task is associated with a resource profile. For example, a task "talk to person" would require the *speaking* interaction and the *hearing* perception resource.

However, the task model is not restricted to modeling tasks. If exceptional environmental conditions have an effect on the user's resources, they can be modeled in the same way. For example if the user is frequently working close to noisy machinery, this may be described as a "noisy environment" task occupying the *hearing* and *speaking* resources just like the "talk to person" task.

3.5 Device Model

With a model of human interaction resources at hand, we can describe the effects of various interaction devices on these resources. Such a description is called a *device profile* (see Figure 4 for an example). The resource demands of an interaction device are not constant throughout its use. There are differences between simply wearing the device and actually using any of its functions. The FreeDigiter, for example, only covers one ear of the user while not in use. Only when used, arm and fingers need to be moved next to it to interact. Other devices like the Winspect Glove [3] have several independent interaction mechanisms. These need to be modeled separately as not every function might be available all of the time.

For this reason, each *device profile* consists of several *resource profiles*. A *wearability resource profile* that describes passive resource demands and continuous requirements of wearing the device. Additionally one *usage resource profile* for each distinct functionality is added that describes the extra resource demands and requirements of using that functionality in addition to simply wearing the device.

A single interaction device might also be used in different ways. Textile buttons as in [25] for example can be attached to the user's clothes in almost any place. But a different placement of the button, also influences the resources required to wear and use the device. Right and left handed version of a device are another case. Currently every possible configuration needs to be described in a separate *device class*. However, these additional *device classes* can be generated using templates.

Apart from learning about times at which a device can be used in a given task situation, it is also necessary to know how such a device can be used in an application. Defining and classifying the device-machine interface has a longstanding tradition in HCI and has been well researched. Buxton [5] provided one of the early taxonomies that was later refined and extended by Card et al. [6, 7]. Lipscomb et al. [14] developed a taxonomy of device characteristics that can be used to further classify input devices. However, the focus of the work presented here is on the human-device interface. Therefore describing the device-computer interface was not necessary. Integrating device interaction capabilities into the device selection process will be a subject for future work.

4. APPLICATIONS

Now that the underlying model has been explained in detail, this chapter describes several applications. All examples are based on the endoscopy examination scenario briefly described in the introduction. The knowledge gained by analyzing existing wearable interaction devices can help structuring observations early in the design process. The task traces generated by these observations can then be used to simulate the situation in the lab and compute compatible interaction devices. Furthermore, the model can be used to add a new dimension to compare wearable interaction devices.

4.1 Structure User Observations

The human resources model provides a framework for focused user observations. A user observations will only reveal interesting findings if the observer is looking for the right things. However, what an observation is focused on largely depends on the observer's experience. Therefore, s/he needs to know all the interaction devices that might be considered before even starting the observations. With the number of different devices available this is almost impossible. However, the model presented here condenses the requirements of a large number of different devices, making observations possible that can be used to determine the usefulness of a large number of devices.

During an initial observation the main tasks of the scenario are identified. To achieve the right level of granularity each of the tasks is analyzed. A task is divided into subtasks if it uses multiple interaction resources that are not used syn-

```
<deviceclass name="gesture pendant">
  <wearing name="wearing">
    <covers what="body.chest.front" object="gesture pendant"/>
    <covers what="body.neck" object="gesture pendant strap"/>
  </wearing>
  <using name="gesture with right hand">
    <activity type="move" what="body.right.arm.hand" touches="true" target="gesture pendant"/>
    <requirement name="mustNotBeCovered" param1="body.chest.front" param2="gesture pendant"/>
  </using>
  <using name="gesture with left hand">
    <activity type="move" what="body.left.arm.hand" touches="true" target="gesture pendant"/>
    <requirement name="mustNotBeCovered" param1="body.chest.front" param2="gesture pendant"/>
  </using>
</deviceclass>
```

Figure 4: XML code describing the resource consumption of the gesture pendant device class. The description contains a resource profile for simply wearing the device and two profiles for different methods of use: The device is suspended from a strap around the neck and hangs in the middle of the chest. It can be used with either hand but requires to touch a button to start the recognition. The camera must not be covered when recognizing gestures.

chronously, i.e. started and stopped at the same time. In the endoscopy example, "hold endoscope" and "navigate endoscope" could have been observed as a single task "handle endoscope". However, when waiting for something the right hand is not used for a short period. Therefore, the task has been split into two separate subtasks. This approach ensures the right level of detail for further analysis, while preserving high level information.

After the initial list of tasks has been constructed, it can be used to focus direct observations using field-coding software or offline video analysis. Independent of the method of gathering data, the results of observing a single situation are called a task trace. Figure 5 shows an example trace of the endoscopy scenario. Such a trace represents an actual instance of the situation that is the goal of our design activities.

4.2 Computing Device Compatibility

The compatibility of the devices in the library is computed by simulating the target situation based on a task trace and its associated task model. The devices are integrated into this simulation to identify any conflicts. Each device is tested on its own. First, a device's wearability during the example trace is computed. Starting with all resources available the device's *wearability resource profile* is applied to the model. Afterwards, the whole trace is simulated, applying and removing resource profiles according to the trace and task model. After each step all the requirements are verified. If any of the requirements fails or if there are any problems applying or removing a resource profile, the device is not wearable in the given situation. If the whole trace can be completed without problems, the device is considered wearable.

Each wearable device is now simulated again to determine periods during the trace where any of the device's functionalities could be used. The simulation is again started by applying the device's *wearability resource profile.* Then again the trace is simulated step-by-step. However, this time after each step, the appropriate *using resource profile* is applied and tested for compatibility. If there are no conflicts, the device is considered usable until the next task starts or stops. The using profile is removed again before the trace's next step is simulated.

Figure 5 shows the result of this procedure for the endoscopy example. For each device that is considered wearable, one line per functionality is added to the bottom of the diagram. Bars in these lines indicate periods where that functionality is considered usable in terms of available modalities/resources.

As can be seen in Figure 5, the magnetic switch, the FreeDigiter, the forearm mounted keyboard and a headset are considered wearable with regards to this trace. However, only the magnetic switch on the right arm, the FreeDigiter and the headset can be used during the actual examination in the middle of the trace. Other devices like the Twiddler do not appear, because they conflict with the use of latex gloves.

A designer can learn from this simulation that there are brief times during the examination where complex interaction seems to be possible using the user's right hand and touch-free interaction. Voice interaction is also possible, but because the doctor frequently speaks with patient and nurse, special care needs to be taken. With that information in mind, the designer can now select one or more interaction methods using the devices identified and build a prototype for user evaluations.

4.3 Comparing Devices

Up to today much of the research in wearable and mobile interaction devices has been driven by technology. If a device's novelty factor comes from its technical details, there is most often no need to compare against other devices with a similar functionality. However, as the field progresses and matures, new devices will have to compete against established techniques for the same class of input (e.g. 2D pointing). Typically usability and task performance are main factors for such a comparison. However, in wearable computing scenarios the device with the best task performance might not be the best choice for a given situation. This is because the type of modalities used in conjunction with the primary task has a strong influence on the overall task performance. The Twiddler, for example, has a good per-

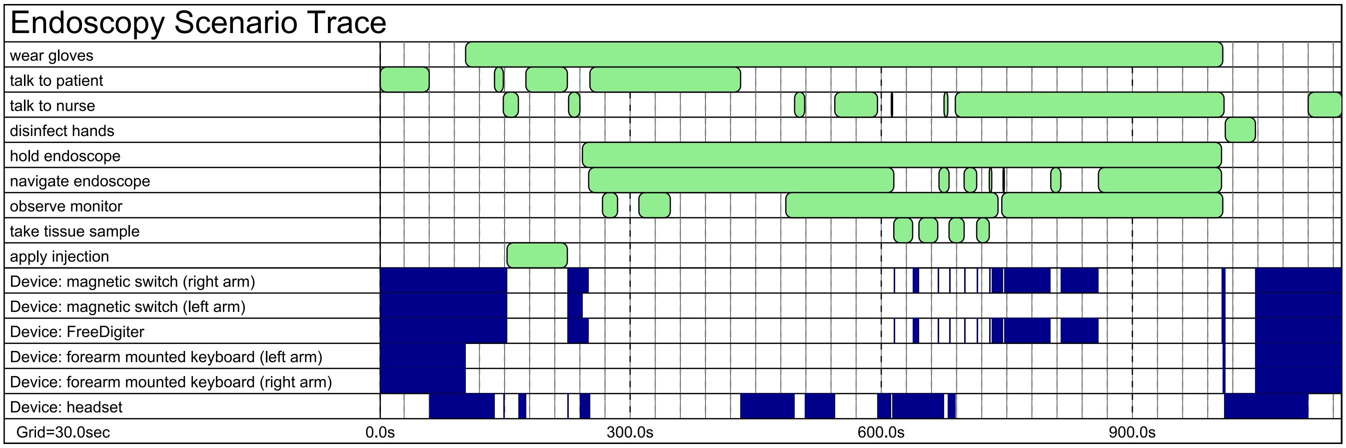

Figure 5: Example trace of parts of an endoscopy examination. Observed tasks are shown by light green bars. Devices listed are considered wearable in this situation and dark blue bars indicate periods where a function of that device is usable. (Additional devices removed for brevity.)

formance for typing text. However the way it is attached to the hand prevents the user from using this hand for other tasks. In a situation where the user's primary task can benefit from using both hands instead of only one, a forearm mounted keyboard might be a better choice. The device model presented here captures a device's resource demands and can be used as an additional factor when comparing interaction devices for the same class of input.

5. CONCLUSIONS

We have presented a model of human interaction resources relevant for multimodal wearable interaction based on a survey of research papers on wearable interaction devices. The model serves two main purposes. First, focusing field studies and user observations to provide higher quality data with respect to designing wearable interaction. Second, it can be used to model interaction device's resource demands. These device descriptions together with the task traces derived from the user observations can be used to simulate the use of a specific device under the constraints of a specific primary task. This leads to a preselection of suitable interaction devices, ultimately helping the designer to design an effective multimodal interaction with respect to the user's primary task.

According to Beaudouin-Lafon, an interaction model needs to be descriptive, comparative and generative [1]. We have shown that our model is descriptive, because it can be used to describe existing solutions from the wearable computing design space. With respect to the modalities used by a system, solutions can be compared, therefore the model is also comparative. Furthermore, our model facilitates the design of systems using new device combinations, partially fulfilling the requirement of a generative model. However, the conception of new devices is supported if the designer investigates the resource combinations unused by existing devices.

6. FUTURE WORK

The model currently only captures the user's perceptual and motor resources. Using cognitive models like QN-MHP by Liu et al. [15], the model could be extended to approximate the effects of the limited cognitive abilities on the overall task performance.

If coupled with wearable sensor based activity recognition, the model could be used to compute the available interaction resources at runtime. The application could then decide on appropriate modalities and interaction strategies on the fly and adapt its behavior accordingly.

7. REFERENCES

[1] M. Beaudouin-Lafon. Instrumental interaction: an interaction model for designing post-wimp user interfaces. In *CHI '00: Proceedings of the SIGCHI conference on Human factors in computing systems*, pages 446–453, New York, NY, USA, 2000. ACM Press.

[2] T. W. Bleser and J. Sibert. Toto: a tool for selecting interaction techniques. In *UIST '90: Proceedings of the 3rd annual ACM SIGGRAPH symposium on User interface software and technology*, pages 135–142, New York, NY, USA, 1990. ACM Press.

[3] M. Boronowsky, T. Nicolai, C. Schlieder, and A. Schmidt. Winspect: A case study for wearable computing-supported inspection tasks. *Fifth International Symposium on Wearable Computers (ISWCŠ01)*, pages 8–9, 2001.

[4] C. Bürgy. *An Interaction Constraints Model for Mobile and Wearable Computer-Aided Engineering Systems in Industrial Applications.* PhD thesis, Carnegie Mellon University, 2002.

[5] W. Buxton. Lexical and pragmatic considerations of input structures. *SIGGRAPH Comput. Graph.*, 17(1):31–37, 1983.

[6] S. K. Card, J. D. Mackinlay, and G. G. Robertson. The design space of input devices. In *CHI '90: Proceedings of the SIGCHI conference on Human factors in computing systems*, pages 117–124, New York, NY, USA, 1990. ACM Press.

[7] S. K. Card, J. D. Mackinlay, and G. G. Robertson. A morphological analysis of the design space of input devices. *ACM Trans. Inf. Syst.*, 9(2):99–122, 1991.

[8] L. E. Dunne and B. Smyth. Psychophysical elements of wearability. In *CHI '07: Proceedings of the SIGCHI conference on Human factors in computing systems*, pages 299–302, New York, NY, USA, 2007. ACM Press.

[9] M. Fukumoto. A finger-ring shaped wearable handset based on bone-conduction. *Wearable Computers, 2005. Proceedings. Ninth IEEE International Symposium on*, pages 10–13, 2005.

[10] F. Gemperle, C. Kasabach, J. Stivoric, M. Bauer, and R. Martin. Design for wearability. In *ISWC '98: Proceedings of the 2nd IEEE International Symposium on Wearable Computers*, page 116, Washington, DC, USA, 1998. IEEE Computer Society.

[11] B. Howard and S. Howard. Lightglove: Wrist-Worn Virtual Typing and Pointing. *Proceedings of the Fifth International Symposium on Wearable Computers*, pages 172–173, 2001.

[12] A. Jameson and K. Klöckner. User multitasking with mobile multimodal systems. In W. Minker, D. Bühler, and L. Dybkjær, editors, *Spoken Multimodal Human-Computer Dialogue in Mobile Environments*. Kluwer Academic Publishers, Dordrecht, 2004.

[13] T. Klug. Computer aided observations of complex mobile situations. In *CHI '07: CHI '07 extended abstracts on Human factors in computing systems*, pages 2507–2512, New York, NY, USA, 2007. ACM Press.

[14] J. S. Lipscomb and M. E. Pique. Analog input device physical characteristics. *SIGCHI Bull.*, 25(3):40–45, 1993.

[15] Y. Liu, R. Feyen, and O. Tsimhoni. Queueing network-model human processor (qn-mhp): A computational architecture for multitask performance in human-machine systems. *ACM Trans. Comput.-Hum. Interact.*, 13(1):37–70, 2006.

[16] C. Metzger, M. Anderson, and T. Starner. FreeDigiter: A Contact-Free Device for Gesture Control. *Proceedings of the Eighth International Symposium on Wearable Computers (ISWC'04)-Volume 00*, pages 18–21, 2004.

[17] H. Noma, A. Ohmura, N. Kuwahara, and K. Kogure. Wearable sensors for auto-event-recording on medical nursing-user study of ergonomic design. *Wearable Computers, 2004. ISWC 2004. Eighth International Symposium on*, 1.

[18] J. Perng, B. Fisher, S. Hollar, and K. Pister. Acceleration sensing glove (ASG). *Wearable Computers, 1999. Digest of Papers. The Third International Symposium on*, pages 178–180, 1999.

[19] J. Rekimoto. GestureWrist and GesturePad: Unobtrusive Wearable Interaction Devices. *Proceedings of the 5th IEEE International Symposium on Wearable Computers, Zurich, Switzerland*, 2001.

[20] T. Starner. *Wearable Computing and Context Awareness*. PhD thesis, Massachusetts Institute of Technology, May 1999.

[21] T. Starner, J. Auxier, D. Ashbrook, and M. Gandy. The Gesture Pendant: A Self-illuminating, Wearable, Infrared Computer Vision System for Home Automation Control and Medical Monitoring. *International Symposium on Wearable Computing*, 2000.

[22] B. Thomas, K. Grimmer, D. Makovec, J. Zucco, and B. Gunther. Determination of placement of a body-attached mouse as a pointinginput device for wearable computers. *Wearable Computers, 1999. Digest of Papers. The Third International Symposium on*, pages 193–194, 1999.

[23] B. Thomas, S. Tyerman, and K. Grimmer. Evaluation of text input mechanisms for wearable computers. *Virtual Reality*, 3(3):187–199, 1998.

[24] A. Toney, L. Dunne, B. Thomas, and S. Ashdown. A shoulder pad insert vibrotactile display. *Wearable Computers, 2003. Proceedings. Seventh IEEE International Symposium on*, pages 35–44, 2003.

[25] A. Toney, B. Mulley, B. Thomas, and W. Piekarski. Minimal social weight user interactions for wearable computers in business suits. *Wearable Computers, 2002.(ISWC 2002). Proceedings. Sixth International Symposium on*, pages 57–64, 2002.

[26] wearIT@work Project Homepage, http://www.wearitatwork.com/, 7 2007.