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Development of a wearable system to capture team (n>2) interactions in engineering design teams

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Abstract

This paper presents the development and ideas behind a comprehensive system prototype of wearable Radiofrequency transceivers, which, by sending small radio packets between devices, are acting as a proxy for dynamically capturing spontaneous human-human and human-object interactions in complex team scenarios. A boundary condition for the design is to minimize intrusion to a level that is comparable to a standard keycard. The system consists of scalable elements that work as low-power stand-alone pieces without any extra infrastructure. The data can be transferred automatically and wirelessly to a computer for post processing. The quantified data is measured by distance and presence of equipment and people to each other. We give examples based on the data we gathered from a pilot study by tracking a team in a laboratory; provide suggestions on how to post process and visualize the data, how to extract useful knowledge therefrom, and how it could be incorporated afterwards in an organization. The overall intention is to combine the data with inputs of managers' knowledge and inputs from dynamic product data management systems in order to capture and analyze how differences in interactions have a measurable effect on product development process.

Keywords: interaction capturing system, RF transceiver, human-human, human-object

1 Introduction

This paper presents the development and ideas behind a comprehensive system prototype of wearable Radio Frequency (RF) transceivers, which by sending low-energy radio packets between devices are aiming to act as a proxy for dynamically capturing spontaneous human-human and human-object interactions in complex team scenarios. We are focusing on capturing long-term human-human and human-object interactions within the framework of design science (Moggridge et al 2007; Cross, 2001). We define interaction as any form of effect that humans can have to each other or to an object by being at limited vicinity up to the

range of roughly dimensions of a room, such as speaking, touching, being present, manipulating machines, etc.
Engineers design and engineer products in teams thus creating and being dependent on social interactions. With evolving autonomous system capability, we might even consider the human-object interaction becoming as a type of social interaction. Even inside the products there are interactions, based on their own architecture with physical, electrical, and informational (data) interfaces. Modern products are more connected than ever and that is why these interfaces can sometimes be hard to keep track of as a designer without an aid of product data management (PDM) system. Face-to-face interactions still have the key role while designing products even though more and more of the interactions between people happen through some electronic communication devices. Researchers and managers can deduce knowledge from the social interaction patterns that help building better products and optimize team allocation and the building process itself. A useful piece of knowledge is determining which design-interfaces are given enough attention and whether there are some that are not given enough attention. For example, if two groups each are designing a component that has an interface in between the two, hypothetically, one can deduce a correlation between face-to-face time spent together between the members of participating design groups and sufficient interface attention. In this case we cannot be sure whether exactly right information is exchanged or not, but certainly there is a higher chance of the interface related conversations than when there was no interaction at all between the group members. This example elaborates our probabilistic view about the problem and what we are aiming to achieve.
Earlier in our research, interactions were recorded either with observation or questionnaire methods (Vignoli et al, 2013). Research has shown that even using a slightly imprecise device to collect interactions is a more reliable and effective method comparing to self-reporting (Liu et al., 2013). Nevertheless, the current solutions that measure face-to-face interactions often require extra infrastructure built around the devices. This means that the systems are not easy to move from one place to another since it is taking a lot of man-hours to set up (Tang, 1991). For example a large team used up to 24 hours to setup the Open Beacon system for a conference and was present during the data capturing (Barrat et al, 2008). There are also devices which aim is to collect a richer variety of data with the purpose of modelling interactions and their context with higher precision. An example of such a device is the "Sociometric badge" created by Alex Pentland's group from MIT (Waber et al 2007). These devices are used to understand social systems in working environments, but as they are capable of collecting information (the badge collects the audio, motion, and location data of the wearer), they are not applicable for all of the use cases in the industry, for example for confideliaty reasons.
There is a need for an independent and portable system that gathers interaction information, that can be shipped out to any given target organization, and requires very little setup time. We address this need and the requirements in this paper by proposing the wearable prototype system that is used as a proxy for dynamically capturing spontaneous human-human interactions in complex team scenarios and discussing of a pilot study. Special consideration is given to robustness, scalability and simplicity for the design of the wearable system.

2 The System

In this section we present our concept of the wearable system to capture a proxy of team interactions and describe the component choices of the first prototype system and explain the working principle.

2.1 Network topography

We had two options to go for the higher level system design that was discussed in our earlier research (Sjöman et al 2015). Either we would have a network of base stations with actors exchanging proximity information through the network, or a dynamic mesh network that would allow any actor to join or leave the network at any given time. This train of thought was revealed not to be the only way of solving the problem. We understood that we do not really need a constant network between devices, but only the proximity information with a certain refresh rate. This led us to choose the third option, the broadcast model, where each device act as a transmitter and a receiver subsequently. By broadcasting we mean that each device is broadcasting its own ID blindly to the vicinity, without expecting any answer. Each receiver device has the responsibility to record all the received IDs and thus creating part of the perception of the network. In the next sections we explain our choices of technology.

2.2 Technology

We started with testing multiple prototypes on different technologies. After tests sensing proximity through distance what low energy radio packets travel seemed to be the most promising with simple scalable idea. We got the principle to work with three devices and decided to continue from there (Sjöman et al 2015). Based on this we decided to focus on radio frequency (RF) transmitters. Next we describe the building blocks of our prototype in detail.

2.3 Components

We used a Light Blue Bean microcontroller, based on the ATmega 328 microprocessor, as a base for the prototype because it is light, simple to iterate with, has low power consumption and is readily available. It is also reprogrammable via Bluetooth and is supported by an extensive open-source software community.

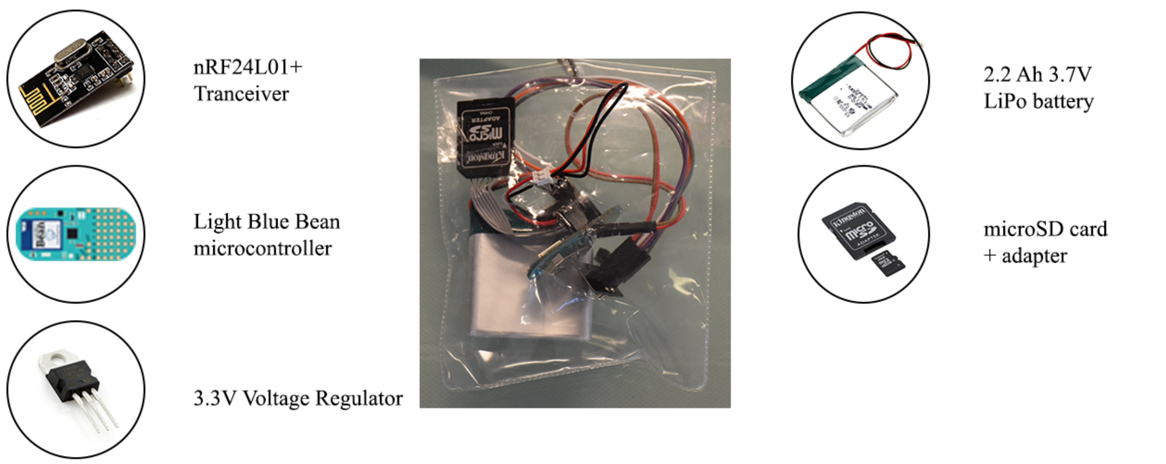

Figure 1. The device consists of nRF24L01+ RF transceiver chip from Nordic Semiconductors, a Light Blue Bean microcontroller, a microSD card with an adapter, 3.3V Voltage regulator and a 2.2 Ah LiPo battery.

For communication between the boards we used the Nordic nRF24L01+ (Nordic Semiconductor, nRF24L01+ 2.4GHz Antenna Wireless Transceiver Module), which is a highly integrated, ultra low power 2Mbps RF transceiver for the 2.4GHz Industrial, Scientific and Medical band (It has 11.3mA power consumption when transmitting at 0dBm output power). This chip is developed by Trondheim based Nordic Semiconductor, and is widely used in wireless applications such as keyboards and mice (Semiconductor, 2007). It has a well-established role as a reliable component in the field of low-power wireless sensor networks (Sonavane et al 2010). The wearable stores the received ID and proximity data locally on an SD card. Both nRF24L01+ and SD card share the same Serial Peripheral Interface Bus (SPI bus). The board is powered by a 3.7V, 2.2 Ah LiPo battery (PL805050P) that is brought down to 3.3V by a voltage regulator (LD1117). A fully charged battery is enough to power the device for at least 48 hours (average consumption 38 mA with four other devices constantly present). The prototype was enclosed in a plastic bag, and sealed with the lock of a necklace. The bag measures 11 x 12 x 3 cm and the prototype altogether weights 48 grams. No optimization is done in terms of size or battery life. Figure 1. depicts the components of one device.

The Light Blue Bean microcontroller contains also components that were not used in this project, such as an accelerometer, temperature sensor and Bluetooth module. The Bluetooth module can emulate a serial connection between the computer and the microcontroller but was used only for debugging, not in the actual application. We used the principle of rapid prototyping. The whole system is built in modular but non-optimal way in order to quickly find out requirements of the system with the task at hand. This way, both software and hardware is easy to test and develop in iterations. The initial tests of the principle were made with nRF24L01+ tranceivers mounted to two Arduino Uno's without an SD card before the system level tests. In the system level, the Light Blue Bean microcontroller was chosen because of the ability of being programmed over Bluetooth and thus making it easier to iterate multiple devices simultaneously. Also other Arduino based microcontrollers were tested, such as Pro Trinket 3V/12Mhz, but because of the low speed of iterating due to lack of a proper debugging channel (two-way USB serial connection), the development was conducted with other boards. The next development version of the prototype is considered to be based on Pro Trinkets. In the next sections we describe what the system consists of and how do the devices work in principle.

2.4 System overview

The system consists of a number of devices with basically similar hardware (with the exception of having an SD card or not), but with three different software variations. The first variation has the capability of sending and receiving radio packets and saving them to an SD card. The second variation is without an SD card and used to tag mainly rooms or objects. The third variation is a base station that can also act as a room or object tag, but also sends a timestamp every tenth second to all devices nearby. In our case it gets the correct time stamp from timeservers in the Internet through a Raspberry Pi microcomputer that is connected to the microcontroller by a serial connection, but of course other ways of updating the time can be applied. The third variation can also be used for downloading data from the devices and uploading it to the Internet. The base station enables more accurate time stamping and automated data flow to specified server, but it is not required in order the system to work.

2.5 The working principle

In general, each device in the system records the identity of the nearby devices by using the RF transceiver while transmitting its own identity. It sends out its own unique ID, representing a person, and receives IDs from others in the proximity combined with the power level that the radio packet was sent out. The next sub sections explain the concepts of the principle.

2.5.1 Power Level

NRF24L01+ transceiver can send with four Power Amplifier (PA) levels. By consequently after other through sending on all four levels, and include which PA level is being used in the data packet, the receiving RF module can see at which of the four transmitting levels it receives powerfully enough and use that as a proximity estimator. The estimated distances seen in Table 1. are experimentally determined with limited sample size.

Table 1. NRF24L01+ transceiver output power settings combined with power consumption and travel distance estimations. Table retrieved from Sjöman et al, 2015.

Power Amplifier Level	RF output power	DC current consumption	Distance (est.)
3	0 dBm	11.3 mA	5 - 11 m
2	-6 dBm	9.0 mA	3 - 5 m
1	-12 dBm	7.5 mA	1.5 - 3 m
0	-18 dBm	7.0 mA	0 - 1.5 m

2.5.2 Sending Bursts

The basic working principle is that every device multicasts a burst of four messages that have all the different power levels from 0 to 3 with a random interval of 4 to 5 seconds between each burst. The individual messages within these bursts are sent with 80ms interval. This interval is based on experimenting with different delays. Since different actions in the code and hardware take time to execute and we do not want the receiver to waste any time, this was found to be a well working interval.

2.5.3 Receiving and Reacting

While not transmitting, the transceivers will be in receive mode and listen to other devices that are nearby. The detection of which power level a device is receiving is a combination of the number in the received data packet, which PA level the packet was sent by the transceiver, and the current signal strength value of the receiver. The NRF24L01+ chip has a very limited receive signal strength indicator, so we had to be creative how to measure the distance. To be precise, we use the Received Power Detector (RPD) of the chip, that triggers at received power levels above -64 dBm that are present in the RF channel one receives on. If this power level is achieved, then the Boolean RPD gets value 1. If the received power is less than -64 dBm, then RDP gets value 0. The RPD can be read out at any time while the nRF24L01+ is in receive-mode. This offers a snapshot of the current received power level in the channel. The RPD status is latched when a valid packet is received, which then indicates the signal strength from the transmitter. This RPD status is saved to the SD card combined with every packet received. The receiver gain varies over temperature, which means that the RPD threshold also varies over temperature. The RPD threshold value is reduced by 5dB at T = -40°C and increased by + 5dB at 85°C.(Semiconductor, 2007).

2.5.4 Storing

The System uses a microSD card to store the received packets and is connected to the SPI bus. The system uses an array buffer to collect received messages from nearby, waits until the buffer is full, and writes the messages to the SD card less frequently than packets are received, in order to avoid the time consuming operation of writing to the SD card. Writing to the SD card takes around 150-300 ms and during that time the transceiver cannot receive or transfer anything to its internal buffer, so those messages sent during writing period are lost and not written to the data storage.

2.5.5 Transfering data for analyzing

As the transceiver is designed for transmitting large amounts of data wirelessly, we envisioned that the easiest for the user is just that a base station sends a request of uploading each devices data that is collected during or end of the day and dynamically keeps track of the data sent. This feature is not yet implemented but the data from the SD cards is extracted manually.

2.5.6 Time syncing

Time stamping and syncing of the data is one of the challenges when creating parts of an image of a dynamic social network. We decided to tackle it by using a Unix time stamp (a number representing the amount of seconds passed since January 1st 1970, which is commonly used as a way to store time) that is broadcasted through the same radio packets by one selected device that is connected to the Internet. We just use a packet with a different header than the “proximity packets” and handle those packets differently while received in order to sync the clock of the microcontroller. The advantage of this approach is that every device is receiving the same time stamp wirelessly without any extra hardware added to devices, such as a real time clock.

2.5.7 Data overview

As mentioned earlier, the device stores the data on an SD card. We had an option to write some prefiltering already for the lower level of the program while receiving packets, but we decided to handle filtering completely during post-processing. This way we would not miss any opportunity to explore the data set differently than planned due to prefiltering. That is why the devices store every received packet to a file with time stamp and signal values without filtering. From Figure 2. one can see five different columns of a raw data file where the first one is unix timestamp. The second column is the ID of the receiver. The third column is the ID of the transmitter. The fourth column is power level included in the packet and the fifth column is the boolean value from the RPD function which determines the power level, and subsequent distances the transmitter is sending from. In this particular situation we can observe that there are four devices near the ID number 102, of which 103, 104 and 105 are max 1,5 meters away and device with ID 66 is between 1,5 and 3 meters away, since power level 0 is not observed with more than -64 dBm in the receiving channel as explained in the section 2.5.1.

1456479212	102	66	0	0
1456479212	102	104	0	1
1456479212	102	104	1	1
1456479212	102	104	2	1
1456479212	102	66	1	1
1456479212	102	104	3	1
1456479212	102	66	2	1
1456479213	102	105	0	1
1456479213	102	105	1	1
1456479213	102	105	2	1
1456479213	102	105	3	1
1456479213	102	103	0	1
1456479213	102	66	3	1
1456479213	102	103	1	1
1456479213	102	103	2	1
1456479213	102	103	3	1
1456479216	102	66	0	0

Figure 2. Partial view of the raw data out of the device number 102 while having 104, 105, 103 in close range in room 66. The first column is time, the second is the receiver, the third is transmitter, the fourth column is the signal strength and the fifth column is

the Boolean value from the RPD function, defining whether the signal was received on the power level it was sent from.

2.6 Limitations

We made a stationary experiment in order to have an estimate of packet loss and the ability to recognise different distances with the devices in a laboratory environment. We ran a 14 hours long (one night) experiment with four devices in the same room at constant distances. The result of the experiment was that 97,90 % of the packets were received, containing the right distance information. This is of course only a static experiment in an empty room and a lot more packets will be lost during the actual use cases in office and workshop environments. Absolutely speaking, there will be a large amount of false positives that will add noise to the data set, but relatively speaking there should not be a significant effect to the overall results gained using the devices, as we collect data over a long period of time.
At the moment the power consumption is not on optimized level, but this is explainable since we are using only off the shelf components that are not optimized for this purpose. Furthermore we are using the Bluetooth adversitising features of the microcontroller that consume a lot of energy, but are unnecessary for this application in a real use case scenario. Now they are only used for developing and debugging.
The price of the components used also reflects the way the components are chosen. We chose the most available components with a consumer price at low volume. All together the price of a device is around $40. A great deal of the price is coming from the Light Blue Bean microcontroller that has features that our product is not using, and a board with similar functions can be bought for a lower price. For now though, the Light Blue Bean microcontroller has been really useful since it is easy to prototype with as it is does not require any wires to reprogram.
Initially we hypothesized that these devices could be worn as a person or be connected to a tool or a room. However, sometimes the large range of the radiofrequency transceivers made this task difficult, limiting the resolution of our data. The higher power levels also seemed to go through floors and thus add uncertainty to the quality of the data.
Waber et al. (2007) had similar kind of issues with their Bluetooth system and they took a different approach to the analysis. They used a probabilistic method to determine what other badges were in the area, since closer devices are detected more often. They ran a five-minute window over the data and detect it as an interaction only if 30% of this time window was populated with the signal from another badge or device (Waber et al, 2007). We have to address these issues while developing the system further.

3 Pilot study

The pilot study was conducted within our laboratory and with the consent of the subjects. Six to eight devices were logging daily routines of persons affilitiated with our lab on four different days. The purpose of the pilot study was to gain a deeper understanding of how the system works, acquire some data for further analysis, spot possible errors and error sources and explore insights on how the system could be developed to a next level.

3.1 Results and analysis of the Pilot study

The are many tools that can be used to analyze the data. For this kind of data for example network analysis can be used. Our focus is on long-term studies that will show over time how people are behaving and interacting together, but also with different objects. The data entries have a time stamp with the resolution of one second, so also time variant analysis and patterns over time can be mined from the data sets. We are left with a set of questions to answer for the further experiments. How can one define an interaction based on proximity and time? Can we use different distances as an indicator of the quality of the interaction? Can we somehow compare these different interaction types? Is there a way to define different intensity interactions through the system? Could those 30 seconds intense interactions with closer range yield similar results productivity-wise as longer time spent in further distance? Figure 3. provides a snapshot of a study and its results after the first day of the experiment. A clear difference can be seen between how much users use the rooms and how much time they are spending with each other. For example, there is a room called M66 and different persons where the width of the arrow represents the weight of the relationship during that time period of the experiment in the left side of the figure. Also, we are able to for example collect how many times and how long time participants spend with a tool. In the case of this figure, with the coffee machine, but it could be anything else as well.

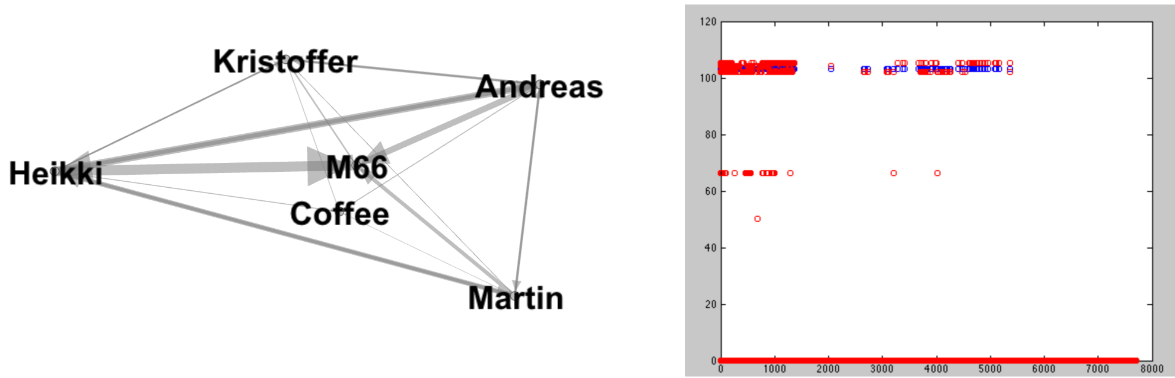

Figure 3. The data is a snapshot of one day in the office and shows how much time has each device spent in the proximity of each other. Meta data has been connected to the data set in order to provide a better understanding of who is interacting most within the group. The left side of the picture is a network analysis, and the right side is the timeline view of the dataset.

We also found some outliers of the data where some of the transceivers did simply not work for some time and measured meaningless data. Part of the aim of the study was to find inconsistencies and possible fails in the system and figure out development suggestions. For example, after the first tests we moved the frequency of the radios 18 MHz up in the band to avoid the interference of present Wi-Fi networks that operate on close frequencies. This seemed to yield better results in the form of less lost packets.
Interpreting the data is about asking the right questions and adding context knowledge. This is where we are only starting to understand what are the possibilities here. In the discussion section we open this topic.

4 Discussion and conclusions

The first question that needs to be addressed is, whether or not it is possible to measure interaction this way? Is the proxy giving real results? Before post processing, the data only contains the received power levels and thus has to be filtered, for example to recognise possible interactions. How to assess the thresholds for the data is another question, since it is unknown what values of the proxy create a valid interaction? There is certainly some indication and correlation with time spent close to each other and interaction, but how strong of a correlation this is, is subject to later research with secondary methods e.g. video recordings in order confirm the results. Then we can start to discuss of probabilities that interaction occur and create some guide lines to interpret data. We would also like to find answers to questions like how to value short but intense interactions against long but not that intense interactions. We are restricted by the technology we used to four different distance ranges, but we believe that they are precise enough to be able to mine meaningful knowledge out of the data.

Our aim is, that by showing the data and discussing the use cases, to invite researchers to think in new ways of using this system. We are aware that there is infinite amount of contexts it could be applied to, and definitely other ways to interpret the data. Also, as we want to keep the system open, so that we can easily adjust to the different needs of scholars. We propose this as a mean of gathering also quantified data instead of only qualitative data. We are interested in hearing suggestions from the community on how to post process and visualize the data, how to extract useful knowledge therefrom, how it could afterwards be incorporated in an organization, and whether he data can be used to enhance team interactions and see patterns during the product developments process. It would be also interesting to think of new ways of combine this data with other sources.

What is it that we learn from the data? We would like to know if it is the state of the interaction or change of the state more important and what is more interesting in each case. We can start using data mining techniques for the data sets and start looking for frequencies that different actions happen. We can see if there is some pair of actions that always happen together. Also it is interesting if there are actions that happen always in the same order but have some time in between. As a simple example, if researchers spend intensive time in a laboratory for some weeks and after that they spend time only in their room. Can we infer that they have performed an experiment and now are interpreting results or writing a paper about it? The opportunities also include combining different data entries or databases, for example to see if there is a significant difference how much 3D-printer in the laboratory is used after its physical place is changed, or new material is bought. This might open a new way of discovering responses to different deliberate changes in the work environment.

We believe that such a measurement tool will allow us to optimize large teams such that the organizational structure and communication patterns reflect the demands and the architecture of the product itself, as explained in Vignoli et al, 2013, but with less man hours. Also the objectivity of the data is increased since it is gathered by means of devices as opposed to subjective qualitative methods. This device offers us a way to gather quantified data in order to better understand design team function. Later the results can be combined with inputs of managers' knowledge and inputs from dynamic product data management (PDM) systems and we can learn from how differences in interactions have a measurable effect on product development process. Of course this might raise ethical issues if such data is gathered and misused by managers. As researchers we always apply this system on voluntary basis and after some successful experiments we are probably able to observe what are the practical implications of collecting such data also from the ethical point of view.

Now we have a working prototype system. The next steps contain developing an easy-spread system and making it available for design researchers, especially in human-human, human-object research fields and together developing new set of explicit research questions and research methodologies.

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