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DYNAMICALLY CAPTURING ENGINEERING TEAM INTERACTIONS WITH WEARABLE TECHNOLOGY

Sjöman, Heikki (1); Steinert, Martin (1); Kress, Greg (2); Vignoli, Matteo (3)
1: NTNU, Norway; 2: Stanford University, USA; 3: Università di Modena e Reggio Emilia, Italy

Abstract

This paper addresses the need of matching the product architecture and the interactions in design teams. A new method for this of how to build agile design teams was first introduced in 2013. We conducted a method-confirming study during spring 2014 where the same study-setup was tested. An idea of gathering interaction data of this study dynamically with a device occurred and led to prototyping with different technologies and concepts. We built a wearable device that is able to detect proximity of other similar devices in front of it nearby and this acts as a proxy for interaction. The device is based on an open source Arduino platform and a radio frequency transceiver chip. User testing of the proof of concept prototype shew promising results of acceptance and robustness. In future research we should be able to to see in real-time how system components and organizational interactions are in interplay with each other, where are the resources used, and thus learn from it how to build better design teams and manage their allocation and interfaces more effectively throughout the various phases of the product and systems development process.

Keywords: Communication, Design engineering, Visualisation, Quantification, Design Research

Contact:
Heikki Sjöman
NTNU
Engineering Design and Innovation
Norway
heikki.sjoman@ntnu.no

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1 INTRODUCTION

Building Agile Design Teams research was conducted in 2013 where a new method was introduced to build and re-organize high performance design teams (Vignoli et al., 2013). Our group at NTNU Trondheim conducted a confirmatory study of the method during spring 2014 where the same study-setup was tested on a formula-student team (a student engineering race car building competition) within the scope of a master thesis. The method was done on a questionnaire basis that has already allowed managements to transform their team's communication patterns into a visual and more transparent form. The research was continued during summer 2014 with the objective of dynamically capturing live team member interactions by the means of a sensor platform. This led, in collaboration with The Radicand Lab (California, US), to the development of a small prototype that is worn as a necklace. The device uses a radio frequency tag connected to a microcontroller to measure proximity of other devices. This paper aims to present this prototype that is able to act as a proxy for dynamically capturing spontaneous human-human interactions in complex team scenarios and also walks through the development phases of the prototype. This device offers us a way to gather quantified data to better understand how design teams function. We believe that such a measurement tool will allow us to optimize large teams in a way that the organizational structure and communication patterns of the team reflect the demands and the architecture of the product itself. Additionally, it will allow the empirical confirmation of previous studies conducted on the impact of team dynamics and communication patterns on output performance in engineering design teams (Jung, 2012; Kress & Schar, 2011).

Our technical suggestion must be seen as complementary to Alex "Sandy" Pentland´s work on using wearable sensors, to capture organizational phenomena (Lazer et al., 2009; Pentland, 2010a; Pentland 2010b). Based on the more stringent privacy and robustness requirements of a high-end engineering team in a competitive race championship situation, using his Sociometric Badges or mobile telephony sensors was rejected in favor to a more single functionality system with a smaller yet more robust design.

2 METHOD - BUILDING AGILE DESIGN TEAMS

The method, "Building Agile Design Teams", maps out the interface architecture of the product at hand and matches it with team interactions in the design organization. This leads to understanding of how the communication structure is aligned with the product structure (Vignoli et al., 2013). This approach gives us quantitative information in a visual format which will be further used to assess how the team is working, e.g. who is talking to whom, how under or over staffed some teams are or how individuals are coping with their workload. Based on this information, team management can draw conclusions and take actions that benefit the team performance. This chapter aims to give an idea how the method is applied.

The tools used to present the information are a Design Structure Matrix (DSM), which depicts product architecture divided into sub-systems and physical interfaces, a Domain Mapping Matrix (DMM), which is a 2-mode matrix combining product sub-systems and human resources, and Person Interaction Matrix (PIM) that is a representation of the actual communication network. In this paper it is still produced by a questionnaire, but ideally the process is automated by the device we have designed. The physical product interfaces are then matched with group member interactions as depicted in Figure 1.

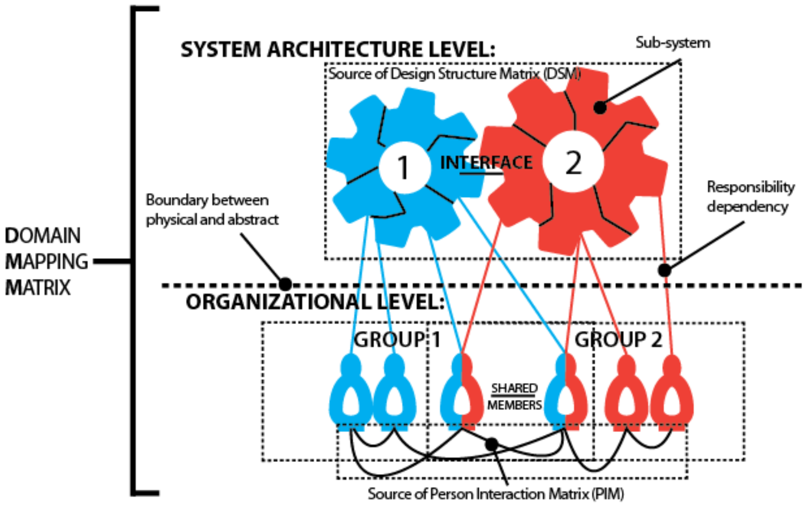

Figure 1. Matrices and their dependencies represented as a picture.

The data is gathered as follows (key subjects bolded):

1. Identify the sub-systems, interfaces and their impacts of the **product** in the whole system and present the results in a Design Structure Matrix (DSM).
2. Analyze the **sub-group memberships** of each member and couple that information with the **product** design. Present the results in a Domain Mapping Matrix (DMM).
3. Conduct a questionnaire (or collect it with a device) of how the different **members** are communicating with each other. Present the results in a Person Interaction Matrix (PIM).
4. Couple the Project Domain Mapping Matrix on **team members** with the design structure (DSM) and human resources (PIM). Present the results in a Missing Communication Matrix (MCM).
5. Couple the Project Domain Mapping Matrix on **components** with the design structure (DSM). Present the results in a Component Alignment Matrix (CAM).

Figure 2. illustrates which data is needed in the process, as well as the respective ingredients of the resulting matrices Component Alignment Matrix (CAM) and Missing Communication Matrix (MCM).

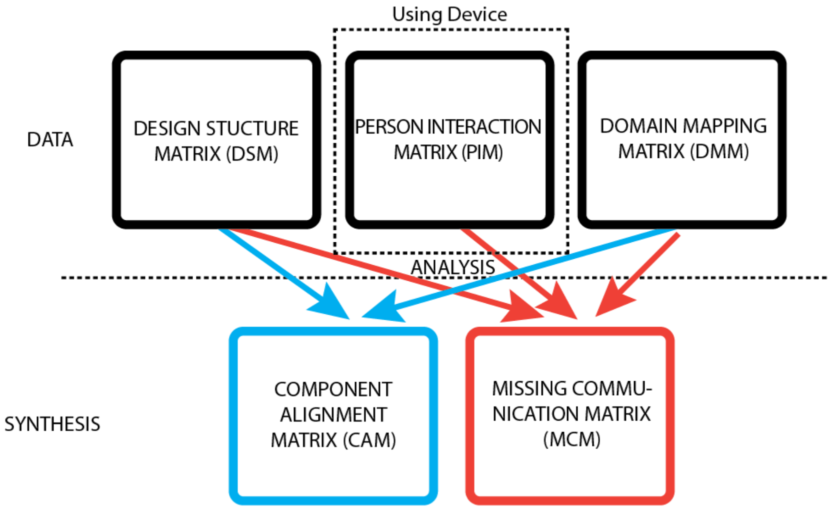

Figure 2. Dependencies and sources of the data in the different matrices.

The method practically takes the information from the product architecture and compares this to how the group memberships are naturally distributed around the product interfaces. If there are two or more shared group memberships within the teams responsible of the interface in question, it is assessed to be a "matched interaction". Otherwise it is defined as a low or high "missing Cooperation". This is described in colors in the Component Alignment Matrix (CAM) and Missing Communication Matrix (MCM) matrices. These threshold values are based on the research of Vignoli et al. (2013) where they decided to use context dependent values of the best possible information of the team. Figure 3 is depicting how the matrices are developed.

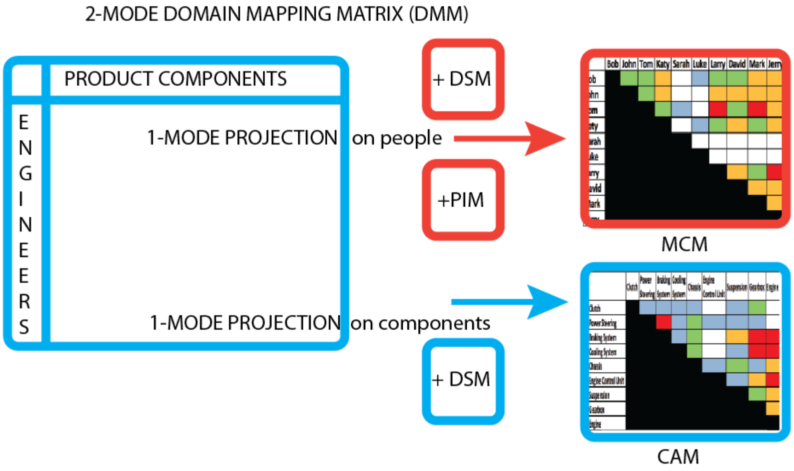

Figure 3. Domain Mapping Matrix projected in its two dimensions.

Vignoli et al. (2013) found that there were some sub-systems that did not have any responsible person at all, some sub-groups had only one member, or sometimes the organizational interfaces failed to match with the product interfaces. The team suffered from having insufficient communication between sub-groups that were not that obviously connected. After the research, the goal was to match the unattended interfaces without changing the collaboration network too radically. This was made possible by modifying the job assignments of the team members slightly, while keeping in mind that the average amount of team memberships of the members should not raise too much as it might negatively affect the performance of the members.

3 CONFIRMATORY PILOT STUDY

Our group took the original method and applied it for another time in a slightly different context where a team of 50 members from different engineering fields built a student racecar. While the original approach was binary, our group added a metric to the Personal Interaction Matrix (PIM) of how often the members of the different design groups discuss with each other in a professional context with a scale of zero to two. The communication was also measured if it was perceived only one way or both ways.

The results of the original method were confirmed and they were yet again very promising. The results were useful as they helped the student racecar team to identify who was doing which tasks and how the information flow was structured and where the communication had its pain points. Also, it helped to discover how the workload was balanced. If the members were part of wrong groups or talking to wrong people it might not be beneficial for the overall performance of the team. For example it was noticed that there was a person who was part of almost all of the teams and thus was good source of information, but at the same time he was overloaded and acted as a bottleneck for many activities. Our study was able to forecast these problems that actually occurred within the team. In addition the feedback from the team was encouraging towards the research. They wished that they could have done the questionnaire, definitions and analysis earlier so that it would have made larger difference in the team performance over the project. The team also wanted to use the method again in the following years.

It has been apparent that using this method takes time and resources and obviously the result is not that accurate when it is made in a paper-based way relying on the memory and (possible biased or subjective) judgment of the participants. What if we could make this interaction tracking dynamic and automatic with little or no intrusion into the subjects' activities? Consequently we focus on the Person Interaction Matrix (PIM), as outlined in Figure 2, and intent to replace it with more accurate empirical real-time data of social interaction. Having a device that captures all spontaneous interactions enables us to make better and more objective decisions on the design team staffing. The next chapter illustrates the journey of discovering a new way of capturing interactions for this research.

4 TECHNICAL PROTOTYPING

The aim of this prototyping is to find an empirical, and quantitative way that generates a large data set of longitudinal data in order to populate the Person Interaction Matrix (PIM). That way we aim to capture and interpret the interactions that are actually happening dynamically in and between engineering design teams. The device capturing the data should be used on a daily basis and it should be able to detect interaction of humans directly or indirectly using for example proximity or voice detection as a proxy. It also should be as minimally intrusive as possible (i.e., if the device was to be carried it should be comfortable and not interfere with daily activities). We decided to prototype different technologies in order to detect and capture when interactions take place. The potential technologies we researched were radio-frequency transceiver tags by Nordic Semiconductor or XBee, Wi-Fi, Bluetooth, infrared and different styles of voice and speech recognition. In order to find the most suitable technology (or combinations thereof) we built a series of prototypes with Arduino and compatible components and sensors. We are aware and understanding that we are not trying to record all possible interactions with high quality, but instead building a device that registers an event every time there is approximation of interaction. We believe that using device like this instead high quality recorder will provide us enough data points to interpret the actual communication patterns and give opportunity to statistically infer the best way to populate teams.

4.1 Proximity Measurements

Proximity measurements were aimed at measuring the relative distance between two people and interpret that as a proxy for an interaction.

4.1.1 Radio Frequency Proximity Measurement

Proximity was initially measured using a breakout board for the nRF24L01+ from Nordic Semiconductors. Four proximity ranges were measured by cycling through the variable power settings of the chip in software. These modules were able to multicast to other modules, but only provided a binary value for receiving a signal at certain strength but not an analog value for what strength the signal came in at. Since body water absorbs very well at the 2.4GHz frequency that the chip is functioning on, and the sensor is worn on the chest as a necklace, the body also acts as a shield for detecting people behind the subject. This gives a natural 180-degree detection angle that is exploited as we decided to use an approximation of that an interaction happens mainly face-to-face. The radiofrequency (RF) tags are accurate enough as they are capable of 1-2m precision of detecting proximity (Cattuto et al., 2010). Kazandjieva et al. (2010) used RF to track 792 high school students and teachers' contact network throughout a day, achieving good results. The RF was chosen to be the most promising technology in detecting proximity.

4.1.2 XBee Proximity Measurement

XBee radio units were also tested in context of detecting proximity. This is a similar technology to the nRF24L01+ chip but is generally better supported by the open-source software community. XBee units provide a one-byte signal strength value. This signal strength provided a finer and bidirectional measurement of distance. XBee technology supports easily mesh networking (broadcasting), which has advantages when expanding to a larger network of devices.

4.1.3 Wi-Fi

Wi-Fi chips can be used to exchange data between the devices themselves. Liu, Jiang, & Striegel (2013) state that Wi-Fi triangulation has accuracy ranging from 3 to 30 meters, where Barrat et al. (2010) write that Wi-Fi have spatial resolution in the order of 10 meters and temporal resolution in the order of 2-5 minutes. In either case the accuracy is too low for our use.

4.1.4 Bluetooth

Bluetooth and Bluetooth Low-Energy (BTLE) technologies are promising candidates for this type of application since they have very fast inquiry procedure that Naya, Futoshi, et al. (2005) were able to use to modified Bluetooth devices to sense location and proximity of people in a hospital context.

4.2 Face-to-face Interaction

We tried a number of methods to measure whether subjects were facing one another, such as infrared and ultrasonic ranging sensors and magnetometers. Our goal was to measure when two people were facing each other as a secondary channel from general proximity measurement. While these sensors worked while directly facing each other the robustness of the measurement was weak and even small deviations from directly face-to-face would cause signal losses. Furthermore we felt that the data obtained was more redundant to the RF proximity data rather than a complementary channel.

4.2.1 Infrared Sensor

Infrared sensors at first required direct line-of-sight without obstructions (Borovoy et al., 1998). A simple infrared sensor was built and worked well when the infrared light and the sensor were directly in line with each other. However, interference from nearby fluorescent lighting caused signal degradation and minor adjustments from directly facing each other would cause false negatives. Future iterations of this method should employ filters and higher angle transmitters and receivers.

4.3 Speech Detection

Proximity alone does not guarantee a spoken interaction, and so a secondary channel is desired that can independently confirm that an interaction has occurred. For this reason we are particularly interested to capture subject verbalization. In combination with proximity data, speech detection would provide a highly accurate means of capturing team member interactions.

4.3.1 Microphone Sound Level

A simple microphone with a built-in pre-amplifier was used to detect sound. Using sound levels alone, we could detect speech, however we also detected any sounds loud enough within the immediate vicinity creating false positives. While the microphone proved to work well at getting a signal to the Arduino, the sound level measurement was not of hight enough quality to clearly distinguish speech and other noise.

4.3.2 Microphone FFT

We implemented a simple Fast Fourier Transform (FFT) routine on the Arduino to breakdown incoming sound into eight frequency components essentially creating a “band pass filter” for the normal vocal frequency range. The chosen library also included built-in noise reduction. This allowed us to detect the wearer speaking but not other ambient noises. In future software iterations the FFT output could be used to implement voice recognition for each user and would then be more reliable at discerning when the wearer is speaking.

5 PROOF OF CONCEPT PROTOTYPE AND EXPERIENCE

This section describes how this device helps us to capture interactions between designers, what it can and cannot do and how it is built. The purpose of this device is to detect and log an event every time in case of an observed interaction between subjects. There is a broad and infinitely nuanced variety and types of interactions, but we focus on direct subject-to-subject spoken interactions. Earlier studies indicate that the approximate distance between individuals in face-to-face interactions is between 1-3 meters (Liu et al., 2013). In order to register all interactions while still keeping false positives to a minimum, a relative high precision of a few meters is necessary.

The raw data from the sensors consist of lines stating who interacted with whom and when. By analyzing this, and defining repeated exchange of data packets as interaction, data can be turned into measurable interactions. In similar experiments (Scholz et al., 2013; Szomszor et al., 2010) face-to-face contact was recorded when the length of a contact was at least 20 seconds. The contact ends when the concerning proximity tags do not detect each other for more than 60 seconds.

5.1 Capabilities

Our objective was not to record all possible interactions with high quality. Instead of building a device that captures an accurate log of interactions within the team, it should, in an efficient manner, create its data set assuredly, not perfectly without flaws, but in such an accuracy that allows us to research underlying phenomena. This system will produce a large data set capable of being analyzed and assessed from a variety of perspectives. Our first goal with the data at hand is to cross-compare the validity of the instrument to the current questionnaire-based approach.

We are focusing on developing the device to have a long battery life and be comfortable and convenient to wear. The device is capable of recognizing and logging the occurrence of interaction events between different individuals. We use radio frequency measurements to determine if the interaction is taking place between 0 to 11 meters with roughly 1,5 meter precision by cycling through available power settings (a form of amplitude modulation). The device records only those interactions that occur approximately face-to-face. This is achieved by the signal attenuation through the body and it prevents effectively the other device to receive the signal outside the 180-degree angle. This was also validated in our experiments. We exploit this feature of RF for our benefit and it makes the design much simpler than with other technologies. One of the prototypes is presented in Figure 4.

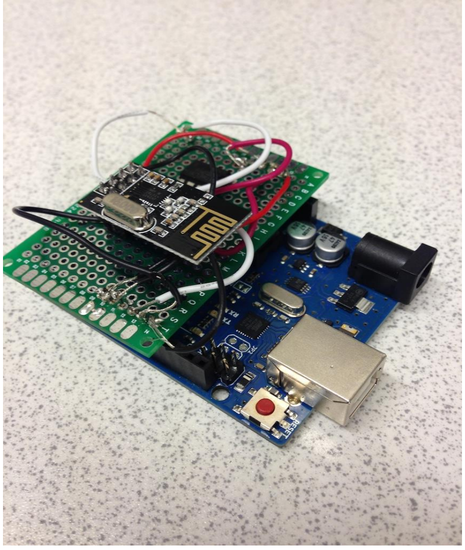

Figure 4. The prototype device consists of an Arduino, RF-transceiver and EEPROM memory (without necklace).

5.2 Technology used

We used an Arduino Uno, based on the AT mega 328 microprocessor, as a base for the prototype because it is light, simple to use and modify, has low power consumption and is readily available. It is also easy to reprogram via USB and is supported by an extensive open-source software community. 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. Also other similar technologies, such as XBee, were considered and tested in order to find out the advantages and limitations of each technology. For storing static data, such as ID of the tag, we used EEPROM (Electrically Erasable Programmable Read Only Memory), which contained 256 Kbytes of data storage. During the testing the device was powered with a regular 9V battery.

5.3 Range testing

The distances achieved with a face-to-face line of sight configuration were respectively roughly 1.5, 3, 5 and 11 meters corresponding to the four built-in signal power levels, which can be set dynamically in software. This means we can determine whether the interaction occurs between 0- 1.5, 1.5-3, 3-5 or 5-11 meters, which should be high enough precision for our use. As mentioned, the range had to be tuned to detect interactions occurring within a few meters. The chosen RF module has four Power Amplifier (PA) levels (min, low, high and max) as shown in Table 1. By multiplexing through sending on all four levels, and include in the data packet which PA level is being used, the receiving RF module can see at which of the four transmitting levels it receives and use that as a proximity estimator. The distances are experimentally determined with limited sample size.

Table 1. RF output power setting for the nRF24L01+

SPI RF-SETUP (RF_PWR)	RF output power	DC current consumption	Distance (est.)
11	0 dBm	11.3 mA	5–11 m
10	-6 dBm	9.0 mA	3–5 m
01	-12 dBm	7.5 mA	1.5– 3 m
00	-18 dBm	7.0 mA	0–1.5 m

The Radicand team implemented a cycling function to continuously measure and record which power level the devices communicate at. The transmitter first tries to send at the lowest power level. If it gets a response, it sends another. If it gets a timeout, it tries one level higher. This continues until reaching the highest level, after which the cycle starts over again. Figure 5 depicts the sample data from a test where two units start close, are then moved apart from each other and back together.

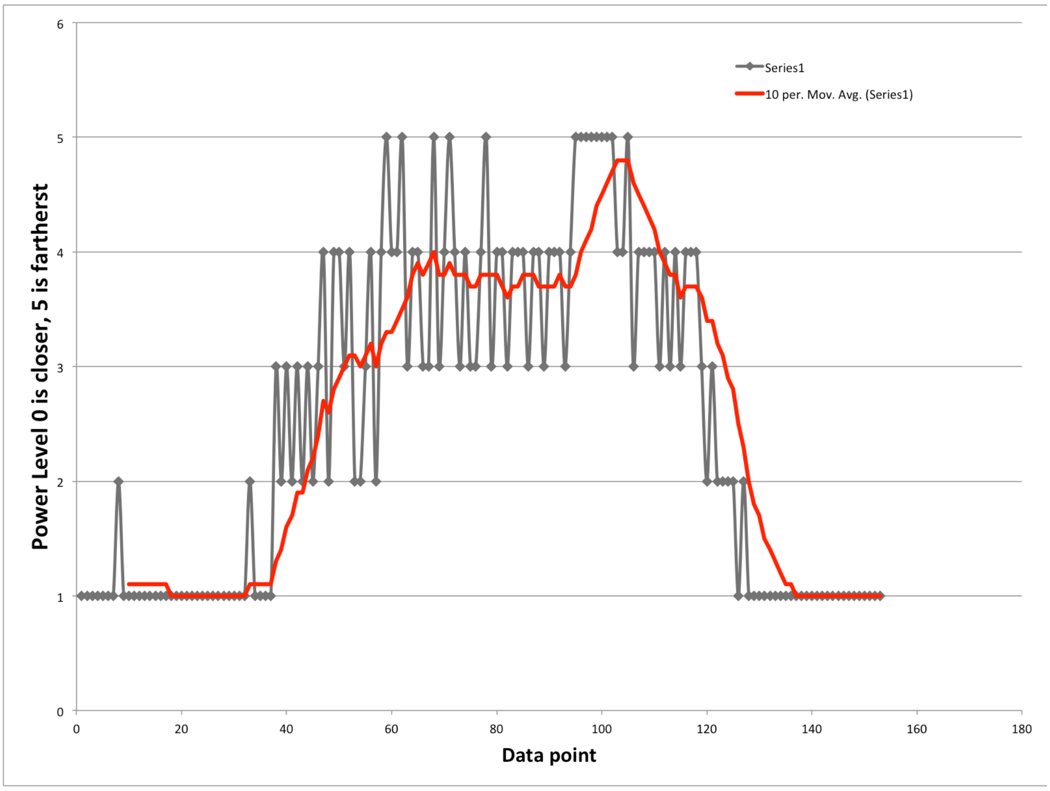

Figure 5. Signal measurement using the nRF24. The test is starting at close distance, then the devices are moving away from each other and then moving back together.

As end result of the range test, the radios were successfully talking to each other — three radios were in the network, each with its own identification number, each cycling through transmission power levels. For each radio, we were successfully sending and receiving messages from the other two.

5.4 User testing

We wanted to make sure that the wearable prototype is comfortable and as minimally intrusive as possible. We performed user testing and gave the device to people to wear for the day at the office to validate that the size and necklace format were acceptable. Building prototypes and testing them was our attempt to discover problems and challenges of using the RF technology to detect proximity and reveal any weaknesses in the concept. No such problems did occur, and the testing showed the technology both provide the temporal and spatial resolution needed. The user feedback was also supporting further development. The overall experience and specifications of nRF24L01+ chip makes it a very powerful candidate in every way for the core of the application. (It is available for less than $1, measuring 28x15 mm, and being power efficient).

6 CONCLUSION

We are instrumenting the missing link between the information of Design Structure Matrix (DSM) and the actual interactions in teams. As we are focused to improve Building Agile Design Teams method by capturing interaction data dynamically, we are also interested to track the Design Structure Matrix (DSM) dynamically. Having built several prototypes in order to identify the most promising technologies, we were able to build a functioning network of devices that detected interaction events by using proximity as a proxy, and also tested some additional augmented sensory channels such as speech detection. Liu et al. (2013) used Bluetooth to measure interaction and concluded: “compared with self-reporting method, our proximity estimation model is a more reliable and effective method to detect face-to-face proximity in daily life”. This result supports our approach as a good candidate for replacing questionnaire-based methods for capturing interactions. If we are using only a proxy and the error is systematic that implies that the proxy will be consistent, whereas the use of speech detection as a verification method, might lower the robustness of the overall solution. Without this secondary channel, we are not capturing verbal interaction audio directly; therefore we cannot be sure if the data reflect true interactions, though all the devices should have the same error and by appropriate filtering we should still be able to extract the communication patterns we are interested in with adequate precision. In addition, the method could also predict what kind of balance is producing the best possible performance between high number shared group memberships and the extra work of communicating among the teams with too few shared members.

7 OUTLOOK

We see several possibilities to enhance the capturing system though further development. There are two high-level options for the system architecture: an ad-hoc network of independent modules that are communicating on the fly with each other, or a master-slave network that has a base station (or stations) acting as a single point of measurement and a central data repository. On the positive side ad-hoc network is flexible, but on the other hand it is more difficult to implement a robust working network of devices in all environments. Our aim is to make a robust and dynamic system where devices can join and leave the mesh network. We can also try out different secondary channels for verifying and improving the quality of the interaction data. It remains to be seen which method will offer the most insight.

The vision is to capture all the data dynamically and with very little intervention of a researcher until the point of analysis. Being able to look at the evolution of the design over time would help us to understand with which varying system focus and within which varying system boundary the design teams are operating during the time span of a development project. This could be solved with using Product data management (PDM) system that records when team members open and edit files and parts. PDM is already embedded in many revision control systems, so the data should easily be available. By doing this, we should be able to see in real-time how system components and organizational interactions are in interplay with each other, where are the resources used, and thus learn from it how to build better design teams and manage their allocation and interfaces more effectively throughout the various phases of the product and systems development process.

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