Exposing Students to a State-of-the-art Problem Through a Capstone Project

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***Abstract*—This Innovative Practice category Full Paper presents the use of a state-of-the-art research problem for a capstone project for third year computer engineering students. In our university, students were given the opportunity to work on a cutting edge problem - indoor navigation systems for the visually impaired. Indoor navigation is challenging because GPS signals cannot be received indoors. It is an area where a large amount of research is ongoing, and hundreds of scientific papers are published every year. For a successful implementation of the system, students had to draw on their knowledge of all the computer engineering concepts, ranging from digital electronic circuits, microprocessors, real-time systems, data structures and algorithms, software engineering, computer networking etc. In addition, students had to evaluate and adopt techniques from existing literature, and adapt them to meet the problem requirements. Thus, the project reinforced their knowledge of fundamentals, while exposing them to a problem with no obvious solution. The main evaluation was conducted as a competition, where students were blindfolded and were required to navigate between two indoor locations. Their system had to download the maps from a server, compute the optimal route to the destination, and students had to navigate there based only on voice and/or haptic commands provided by their system. Some constraints were imposed to ensure that the problem did not get trivialized and accurately represented a real-world scenario. Quantitative and qualitative results from the module feedback surveys showed significant improvement over the previous capstone project. The surveys indicate that the nature of the project and the evaluation process provided adequate challenge and excitement to students, while facilitating effective learning. Students were able to exercise their creativity, and come up with a number of interesting positioning techniques. Such a project ensured that the learning process cemented their understanding of subject fundamentals while addressing a novel research problem that is current, and has a potentially huge societal and commercial impact.**

***Keywords*—Capstone Project, state-of-the-art problem, indoor navigation.**

I. INTRODUCTION

A capstone project is a feature of most undergraduate programs in computer engineering. Marin et al. defines it as "the crowning achievement in a students academic curriculum, which integrates the principles, concepts, and techniques explored in earlier engineering courses" [1]. A capstone project is thus an experiential learning activity that requires students to perform product design, development, testing and documenting, in a single project [2].

In computer engineering programmes, such a project is usually meant to expose students to the development of a large system from conceptualization to its final implementation, involving substantial design and development of hardware and software components. The importance of the capstone project in introducing students to engineering design is well documented in literature - it better prepares graduates for engineering practice [3]. In addition, analytical and problem-solving skills that are key for employability in the industry are often honed through work done in engineering capstone projects [4].

Capstone projects may involve a pre-defined problem, or it may be left to students to select one. Appropriate project selection is a key element of success for a capstone design course [1], yet the project selection task presents perhaps the most challenge to students and faculty alike [2]. Accreditation Board for Engineering and Technology (ABET) Criterion 4 [5] specifies that "Students must be prepared for engineering practice through a curriculum culminating in a major design experience based on the knowledge and skills acquired in earlier course work and incorporating appropriate engineering standards and multiple realistic constraints". The selected projects should have a suitable scope such it is reasonable to expect students to be able to execute them within the duration of the course, utilizing the skills and knowledge they possess [6].

Furthermore, capstone projects can vary widely in their complexities, unlike traditional courses which tend to be mostly uniform [6]. Thus, not all capstone project may be conducive in allowing all students to equally meet the learning objectives of a capstone project. Given the complexities involved in students selecting a suitable project, and the difficulty faced in fairly evaluating projects of disparate complexities [6], a fixed theme was selected for the capstone project, so as to minimise the adverse impact of the challenges listed. This is also justified as students have a final year thesis project where they can choose from a wide range of projects or propose their own. Nevertheless, students are given substantial freedom in deciding the overall system architecture, including hardware, software, as well as form factor aspects.

In an engineering capstone project, while students typically go through the entire process of engineering a system, they generally do not deal with an open problem that researchers are still working on. In this paper, we experimented with giving students a state-of-the-art problem to address through their capstone project.

The rest of the paper is organized as follows: Section II provides more details of the indoor navigation problem, which forms the basis of this paper. Section III gives the background and details of the capstone course, and Section IV details the capstone design process. Details of student performance in the course are given in Section V, in which some innovative techniques that students came up with are also discussed. Section VI compares this capstone course to other similar computer engineering capstone projects to highlight the contextual relevance, and provides some recommendations based on our experience. The paper concludes with Section VII.

II. Indoor Navigation Problem

Global Positioning System (GPS) technology has changed the way we go about navigating between places. GPS allows reasonably precise positioning outdoors. While GPS is from the US, other countries have similar positioning systems, such as GLONASS from Russia and Beidou from China. They are all based on satellite signals, and require a view of the sky to receive signals from at least 4 satellites for a successful positioning [7]. Navigation problem is just an extension of a positioning problem, and if the maps of the locality are available, finding the best possible route and providing guidance is not difficult. However, indoor positioning is more challenging, as GPS signals cannot be received indoors. Indoor positioning and navigation has a large body of applications, ranging from automated logistics systems, to being of use to the common man, to being of immense value to the physically challenged.

The indoor positioning problem has been explored by a number of researchers over the past decade or two, and several possible techniques are examined in the literature. Possible localization techniques include dead-reckoning with inertial measurement units, WiFi fingerprinting, trilateration based on various beacons and markers, and fusion of information from these through various algorithms [8]. Inertial navigation is one of the the most popular techniques for indoor localization [9]. It relies on keeping track of every displacement from an initial position, a technique known as dead reckoning. The movement is computed using the fusion of data from sensors such as accelerometers, gyroscopes and compasses. Some systems also use barometers for determining the height. However, sensor readings have finite resolution and are noisy, and since positioning is done through integration of the sensor data, errors accumulate. While techniques such as Kalman filtering are popularly used to minimize the impact of noisy data [10], the typical accuracy is still far from what is practically desirable. However, inertial measurement units can detect steps/strides fairly accurately like a pedometer. This, in conjunction with the heading given by a magnetometer and height given by a barometer, can give reasonable accuracy, a technique known as pedestrian dead reckoning [11].

Another popular indoor localization technique makes use of the ubiquitous WiFi access points (APs). A WiFi course can be used to measure the wireless strengths (RSSI) from each AP, and given a mapping between the MAC addresses and AP locations, it is possible to perform positioning through trilateration [12]. Alternatively, it is possible to map the strengths at various points and use it as a lookup table (fingerprinting) [12]. However, wireless strength varies with the objects in the room and absorption by people. There are some works which use Bluetooth [13] or UWB fingerprints [14]. Other possible options are ultrasound/infrared based wall/obstacle detection, and if there is a precise map of surroundings, it is possible to do positioning using those [15]. Some indoor positioning techniques based on Radio-Frequency Identification (RFID) or optical / visual markers (such as QR codes) have also been reported [16]; however, they may require environmental modifications, and require the subject to always be within range of the marker. Vision based techniques, using computer vision-based object/geometry identification have been proposed as well [17].

III. Background

A. The Capstone course

The capstone project is a semester-long, 6 Modular Credits (MCs; 1 MC implies an investment of 2.5 hours per week) programme, usually taken by third year students in the computer engineering programme. The computer engineering programme in our university is a multi-disciplinary programme where students belong to both the department of electrical and computer engineering, and the department of computer science. The first four semesters mostly involve core courses, and students have an option to take the capstone course in their fifth or sixth semester. A minority does it in their final year, though this is discouraged as it overlaps with the honours thesis project. Students have to go through the core courses such as digital fundamentals, ARM Cortex M3 programming and interfacing, real-time operating systems, and software engineering, before taking this course. The course is co-taught by 2 to 3 lecturers, at least one from each department. The course is conducted using a combination of lectures, design walk-through sessions and laboratory sessions over 13 weeks. Each week, students will be given a short lecture centred on one topic in the syllabus, and how it is to be applied in their project. Students are then to apply what is taught, in their project. This is followed by a design walk-through or laboratory session in the following week. Students are organized into teams of 6 to execute the projects. Through the capstone project, students are able to better appreciate the relevance of the various components in the computer engineering curriculum to large scale computer engineering projects.

B. Learning Outcomes

The learning outcomes of the capstone project are that students should be

- able to apply hardware and software engineering design principles in specifying, architecting and implementing a complex embedded system.
- able to understand team dynamics and successfully manage a reasonably large project.

The course takes the students through product conceptualization, requirements capture, application design, hardware/software partitioning, hardware development, software development, system integration and verification and system commissioning. Students learn from a hands-on project to design and build an embedded system. Emphasis was also made on systematic software engineering practices, as it is key to rendering students ready for the industry [18].

C. Previous Project

The previous project was that of a talking cash register system. Students were expected to build a cash register based on the 8088 processor, which had the ability to read out characters typed on the keypad. The system was also connected to a server through a serial interface, and the server has a database and framework for inventory management. While a cash register and inventory management system is practically useful, students were not excited about the project. Part of it has to do with the fact that a lot of time was spent on connecting the discrete hardware - such as RAM courses, interrupt controllers and communication controllers. Since most systems these days are built around system-on-chips (SoCs), it is no longer important to connect discrete hardware units as it was in the past. We also believe that the lack of excitement has to do with the nature of the problem itself. Hence, it was imperative to design a new capstone project.

IV. Capstone Project Design

There were several considerations for choosing a capstone project theme. Cheville et al. [19] identified some attributes of successful capstone design projects, including "being viewed as worthwhile", being related to field of specialization in engineering, and involving "modern and emerging technologies with which most of the students would have some familiarity". Service learning projects with a potential social impact were more likely to be viewed as worthwhile by students [20]. State-of-the-art problems of a reasonably complex nature with no obvious solution yet are intrinsically exciting while being centred in the computer engineering discipline; thus they motivate students to read widely and build products that may have a real societal impact. Adding a competition element to the evaluation maintains high student engagement and interest; and a fixed project addresses the challenges associated with project selection and allows for fair evaluation. With these considerations in mind, the scope for the project was defined.

A. Project Overview

The theme of the project is *A wearable device to provide in-building navigation guidance for a visually-impaired person*. The eventual product was required to have the following characteristics.

- It should be *wearable*, which could be in the form of a cap, backpack, belt or a walking stick. Weight, form factor and comfort are all criteria to evaluate the usefulness and usability of the device.
- It should provide *path navigation* - it should figure out the path from one point in the building to another and guide the wearer to walk towards the specified endpoint.
- It should be capable of guiding the wearer to *avoid obstacles* along the way. Obstacles may be static or moving.

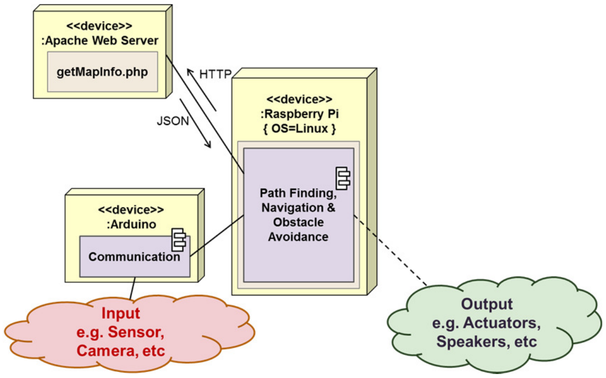

Fig. 1: Overview of the system

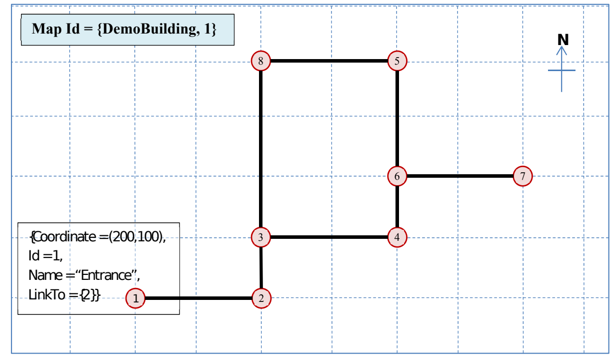

Fig. 2: A graph representing a level of a building

Coordinate	Id	Name	LinkTo
(200, 100)	1	Entrance	2
(400, 100)	2	Room 1	3
(400, 200)	3	Room 2	4, 8
(600, 200)	4	Male Toilet	6
(600, 500)	5	Female Toilet	8, 6
(600, 300)	6	Corridor	4, 5, 7
(800, 300)	7	TO level 2	6
(400, 500)	8	Room 3	3, 5

Fig. 3: Table showing the floor node information

- Elevation detection may be needed to handle staircase, uneven ground or a hole in the ground.

There are several end points in a building to represent possible destinations. Each end point has a unique ID for simplicity. The wearer specifies the unique ID of the starting and destination end points, and the system should be able to help the user navigate between any two points within the building. The floor plan of the building can be retrieved through the Internet. The overview of the system is shown in Fig. 1.

Each team was given a Raspberry Pi single board computer (SBC) and an Arduino Mega microcontroller board. Raspberry Pi is a fairly powerful board for systems requiring mobility, and has low power consumption. Arduino Mega has a large number of onboard controllers/interfaces, making it easier to interface it with sensors and actuators. It is also suitable for real-time processing. Both platforms are characterized by the availability of a large number of libraries built specifically for these boards, and strong online communities/ecosystems, making it easier to create systems around it. A set of standard components including 10 Degrees of Freedom sensors (10 DoF, composed of 3-axis accelerometer, 3-axis gyroscope, 3-axis magnetometer, pressure sensor), ultrasound sensors, WiFi dongle, cameras, level shifters and other basic ICs were provided. Each team was also allowed to purchase additional components/materials subject to a certain budget limit. The system had to be battery-operated, so students were encouraged to use power judiciously.

The user can specify the endpoint through keypad or voice command. The system gives responses to the user through actuators such as speakers or vibration alerts. While there were no restrictions on the mode of interaction with the system, the students were required to take into account the fact that the target users are visually impaired. Hence, popular interfaces such as touchscreens cannot be used in the normal course of operation. There were also no restrictions on the algorithms to be used for path finding, navigation, obstacle avoidance and sensor filtering. Students were encouraged to use a real-time operating system, and received bonus marks for doing so.

1) Path Information Representation: Each level of a building is represented as a graph, as shown in the example in Fig. 2. Locations of interest (LOIs) are represented as a node (vertex) with coordinates (X, Y axes, measured in centimeters), id (integer), name (text) and links to other LOIs, as shown in Fig. 3. Each graph is identified by (building name, level number). The name of a node has no special meaning except for "TO level XXX", which can be used to handle movement between levels of a building. Typically this represents a staircase or connecting pathway between different levels of a building. Note that some nodes may be connected to more than one level, those are represented as "TO level XXX, YYY, .".

2) Map Orientation: Building maps typically do not assume any directional orientation, i.e. the top of map may not correspond to North. To accommodate this, each map now indicates the orientation with a number *northAt*. This number represents the compass North in degrees. For example, if the maps northAt is 0 degrees, North is at the top of the map whereas if the maps northAt is 270 degrees, North is at the right of the map.

3) WiFi Access Points Information: The WiFi base station information, including X, Y coordinates, name and MAC address, are included in the map information. The information is packed together with the basic map information. The graphical view of the map also includes information on the WiFi access point nodes.

The path information is stored in a database on a web server. It can be retrieved from a custom server through the PHP page *getMapInfo.php?Building=AAA&Level=BBB* where AAA is the building name (single word) and BBB is the level (integer). The webpage returns a **J**ava**S**cript **O**bject **N**otation (JSON) object with the following format:

```
{
 "info": {"northAt": North, in degree},
 "map": [ {array of map nodes} ],
 "wifi": [ {array of WiFi AP nodes} ]
}
```

The object is an associative array that contains three major pieces of information, each can be accessed via the key “info”, “map” and “wifi” respectively, as shown in Fig. 4.

V. Evaluation

A. Evaluation Methodology

The project was evaluated continuously over the 13 week semester. In week 4, students were expected to submit a design report detailing their overall system design and high-level subsystem designs, this contributed to 10% of the course grade. There was a progress checkpoint in week 6 with a 5% weight, to ensure that the team was on the path for the 1st prototype, and to ensure that the team reacts to feedback given by the teaching team on the design report. The first prototype was evaluated in week 7 to check if the project was ready at a subsystem level, and carried 20% weight. A second prototype evaluation weighing 25% was conducted in week 11, where the teams were expected to have a more or less complete baseline system. The final evaluation in week 13, which carries the final 40% weight, evaluates the complete and fine-tuned navigation system with extra features, if any.

The final evaluation itself added an element of fun through competition, while the teams could learn from each other about the advantages and disadvantages of various implementations. The various aspects such as path finding, navigation, obstacle avoidance and form factor were evaluated separately. The evaluation was conducted as a competition in which students were required to navigate a given indoor environment while blindfolded; the map could be downloaded from a server at the time of evaluation. One student from each team was required to navigate between two points. The student was required to call out the instructions given by their device and follow them to perform the navigation. The ability of the system to detect dynamic obstacles was tested. Students were also required to tap at the doors of some staff offices, which was instructed to them beforehand, as a checkpoint. Each bump with an obstacle resulted in a penalty.

B. Student Performance in the Course

The new capstone project ran successfully for 3 years. The fact that students knew they would be blindfolded allowed them to be in the shoes of a visually impaired person. Some students interviewed visually impaired people to gain a better understanding of the problems they face. Many students were also very motivated by their ability to possibly give back to society through this project. All teams made use of the inertial sensors in combination with an estimated stride length for positioning. Most teams also made use of WiFi-based trilateration. All teams used ultrasonic distance sensors for obstacle detection. Most teams managed to reach well over half-way through the path, aided by the product they built. In the first iteration of the course, 3 of 21 teams managed to finish the path completely. Some teams managed to use a pressure sensor to detect climbing of steps accurately, allowing for navigation between floors.

Beyond the basic techniques mentioned above, many teams had value-added features. Some teams included infrared detectors in addition to ultrasonic sensors to enhance obstacle detection, especially those obstacles which are sound-absorbing. Some teams implemented value-added features such as the ability to show the live position of the user on a webpage. This could be useful, for example, for a remote caregiver to monitor the visually impaired person. Some teams augmented the inertial navigation/dead reckoning with computer vision-based cues from the environment, which relied on environment modifications such as QR codes on the ceilings. The use had to wear a cap with a camera pointed upwards. Some students also used a ’walking stick’ with a rotary encoder.

C. Student Feedback

The introduction of the new capstone project improved students’ perception of the project over the previous version, which can be inferred from the quantitative and qualitative feedback, especially for the question ‘Overall Opinion of the Course’ as shown in Table I. The overall expected grade did not vary much, as

```
{
"info":{"northAt":"180"},

"map":[
 {"nodeId":"1","x":"200","y":"100","nodeName":"Entrance","linkTo":"2"},
 {"nodeId":"2","x":"400","y":"100","nodeName":"Room 1","linkTo":"3"},
 {"nodeId":"3","x":"400","y":"200","nodeName":"Room 2","linkTo":"4, 8"},
 {"nodeId":"4","x":"600","y":"200","nodeName":"Male Toilet","linkTo":"6"},
 {"nodeId":"5","x":"600","y":"500","nodeName":"Female Toilet","linkTo":"8, 6"},
 {"nodeId":"6","x":"600","y":"300","nodeName":"Corridor","linkTo":"4, 5, 7"},
 {"nodeId":"7","x":"800","y":"300","nodeName":"TO level 2","linkTo":"6"},
 {"nodeId":"8","x":"400","y":"500","nodeName":"Room 3","linkTo":"3, 5"}
],

"wifi":[
 {"nodeId":"1","x":"300","y":"150","nodeName":"ap-101","macAddr":"29:11:A1:8B:C2:D0"},
 {"nodeId":"2","x":"700","y":"270","nodeName":"ap-102","macAddr":"9A:22:5B:1C:D4:5E"},
 {"nodeId":"3","x":"500","y":"500","nodeName":"ap-103","macAddr":"F9:33:0A:92:9C:D9"},
 {"nodeId":"4","x":"500","y":"350","nodeName":"ap-104","macAddr":"B1:44:A6:BB:EC:D0"}
]
}
```


Fig. 4: JSON representation of the table in Fig. 3, with wifi and northAt included

Year	Respondents	Excellent(%)	Good(%)	Satisfactory(%)	Unsatisfactory(%)	Poor(%)	Average Score (Out of 5)
Old Capstone	69	19	39	29	9	4	3.59
New Capstone	49	18	57	22	2	0	3.92

TABLE I: Question 1 : Overall Opinion of the Course (Likert Scale)

Year	Respondents	A(%)	B(%)	C(%)	D(%)	F(%)	Average Score (Out of 5)
Old Capstone	69	36	51	7	4	1	4.14
New Capstone	49	21	69	8	2	0	4.08

TABLE II: Question 2 : Expected Grade for the Course (5 point scale)

Year	Respondents	Very Difficult (%)	Difficult(%)	Average(%)	Easy(%)	Very Easy(%)	Average Score (Out of 5)
Old Capstone	69	46	46	7	0	0	4.39
New Capstone	49	69	29	2	0	0	4.67

TABLE III: Question 3 : Difficulty Level of the Course (Likert Scale)

shown in Table. II. This is perhaps because of the fact that students are aware that the grading is relative, and most of them have a good idea of how they stand with respect to the rest of the team. This is also helped by the transparency in the evaluation process. The perceived difficulty level increased too, which should be expected given that the students are dealing with a challenging problem; this is shown in Table III. There were 127 students in the class for the old capstone, of which 69 responded to the survey. For the new capstone, the number of students in the class and the number of respondents was 102 and 49 respectively.

The students were asked the following two qualitative questions regarding the module:

Q1 What they liked about the module?

Q2 What they did not like about the module?

The qualitative feedback was further analysed to identify the keywords and their occurrences to help future iterations of the module. The frequency of occurrence of certain keywords have been tabulated in Table IV. The students found the project interesting, novel and liked the challenging nature of the requirements and the assessments. At the same time, the challenging and uncertain nature of the project resulted in it being time consuming that was not liked by them.

Some of the selected qualitative feedback from students (positive as well as negative) in the first run of the new capstone project are given below.

- "The course was very helpful in reiterating some of the key concepts that computer engineers learnt in their earlier college years"
- "It was a very fun course to take, building a system from scratch that was actually used in real life situation was the best part"
- "I like how the new structure allow student to think far and wide with little limitation,

Q1 : What they liked about the module?		Q2 : What they did not like about the module?	
Keyword	Unique Occurrences (%)	Keyword	Unique Occurrences (%)
Interesting	33.33	Time Consuming	33.33
Challenging	18.5	Uncertainties	18.5
New	14.7	Difficult	10

TABLE IV: Frequency of Occurrences for Top 3 Keywords in Student Feedback

and how it challenges us to learn something new within a short time, allows student to be creative"

- "The overall experience was awesome. Applied knowledge learnt from previous courses. The satisfaction of creating a system is second to none. Love the autonomy given to students to build the system although there were some restrictions."
- "Focusing on an emergent (new, and especially unsolved) technology is more challenging. The rewards (and possible losses) are greater. It might not be a very good idea as students might be more geared towards developing a new technology in branches, individually, instead of focusing on developing work in a team."
- "The requirement on 'wearable' was not really clear. We felt unfair that some accepted products were not really wearable."
- "This is a new project, many uncertainties are there. Moreover, the profs are also learning and improving the project in phases. This makes the whole project harder to debug and thus a lot of time was wasted due to blindly testing."

Some of the above comments and the keywords analysis were taken into account in the future runs of the course. This includes fine-tuning the specifications and guidelines, and providing more learning materials. Students experienced much excitement and a huge sense of achievement in this project, evident from the large number of students sharing photos and videos of their projects on social media.

D. Issues Encountered

One difficulty encountered was in getting the Raspberry Pi WiFi connected to the university's WPA-Enterprise WiFi. Eventually, with appropriate settings, all students managed to get connected. Another challenge was the estimation of stride length, which is not always uniform. Stride length is affected by factors such as stride frequency [21], which resulted in accumulation of errors in some cases.

From an evaluation perspective, allowing students to use walking sticks with rotary encoders created a perception of unfair advantage to those teams, as noted in a qualitative feedback in the subsection V-C. This was because of the haptic feedback users get from the cane, which can help with navigation like how visually impaired people use it. In the future semesters, a no-contact rule, disallowing any direct or indirect contact with the ground other than feet was imposed. We also disallowed the use of environmental modifications in future semesters, to ensure a level playing field to the extent possible.

VI. Discussions and Recommendations

The design capstone is an important component of the undergraduate degree programs in engineering. The ability to conceptualize, design, implement and operate (CDIO) methodology provides students with an authentic experience of working with state of the art problems [22]. Hylton [23] compared four different approaches to capstone project design including the traditional lecture format, design and build approach, online lecture mode and 1 week intensive format. One of the key conclusions was that students prefer a tangible product that they can learn from. The choice of the state of the art problem in indoor navigation along with the requirement of creating a working prototype follows this format. Zhuang et al. [24] observed that with the introduction of assistive technology to their capstone engineering design, the students' experience of the design process improved steadily. Thus the choice of a socially relevant theme, i.e., designing an in-building navigation guidance for the visually impaired, trains students to be socially responsible engineers while improving their overall experience of the design capstone process.

The successful implementation of the project using Raspberry Pi and Arduino hardware platforms mirrors the experiences Jamieson et al. [25] had in a number of courses in electrical and computer engineering curriculum. This reduced the learning overhead associated with more difficult platforms such as the one we had used in the old capstone project. There were still concerns about the time consuming nature of the project as inferred from the keyword analysis, which is something capstone designers needs to be mindful of. While using a state of the art problem brings in challenges and satisfaction, it also brings in uncertainties in feasibility and expectations, as well as a higher overall difficulty, which could be a concern too when adopting such topics for capstone projects.

VII. Conclusions

A capstone project using a state-of-the-art problem, indoor navigation, was introduced. Qualitative and quantitative results indicate that students learnt a lot in the course. The introduction of the new project added a lot of fun, challenge and excitement for the students. Student are appreciative of the ability to integrate all their previous knowledge to create a working product which has the potential to create immense social impact. Evaluation using a real-life navigation setting for the visually impaired also resulted in students exhibiting better empathy for the user, as well as a competitive spirit. However, setting the 'rules' regarding what is allowed and what is not, proved to be challenging in the initial run of the project. The project could be further improved by exploring other similar problems which train students towards the ultimate goal of engineering - to improve the quality of life of humans, making the world a better place to live, for all.

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