A Web of Things to Reduce Energy Wastage

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Abstract—**Western Australia's economy is largely driven by the extraction and processing industry. Caused by inhospitable climate and living conditions in the remote regions, where the vast majority of the natural resources are found, housing needs for personnel are both difficult and costly to meet. The provision of energy accounts for a big part of this since it often requires the transportation of large quantities of fuel over long distances. This would suggest a responsible and effective use of energy, but often the opposite is the case. Excessive wastage is more the rule than the exception. This results not only in high costs but also considerable greenhouse gas emissions. To address these issues, we present a distributed system which drastically reduces the amount of energy wastage without affecting the quality of living of the residents. By building the system to form a Web of Things we try to simplify its management, assure its scalability, and hope to foster its use in unanticipated ways.**

Keywords—***Distributed system; Web services; Web of Things; Home automation; Energy management; SEREDASj; SmartCamp***

I. INTRODUCTION

Western Australia is Australia's largest state and accounts for almost one-third of the continent, making it larger than Western Europe. Due to the abundance of natural resources its economy is predominantly driven by the extraction and processing of a wide range of commodities such as iron ore, petroleum, gold, alumina, and nickel. But, while most of the population inhabits coastal areas, the vast majority of the natural resources are found in remote regions in the state's interior which has a very hot climate and very limited water resources. Even though cost of building the necessary infrastructure is prohibitive compared to the coastal regions, mining companies have invested heavily in these regions, in terms of, both, equipment and personnel. Since housing needs are difficult and costly to meet due to the inhospitable climate and living conditions most of the personnel in those areas is fly-in, fly-out.

Fly-in, fly-out is an employment scheme where employees are flown to the work site rather than relocating them and their families to a town near to the work site. They work for a number of days and are then flown back to their home town for a number of days of rest. Generally, this is cheaper for the employer than establishing permanent communities for their workers and families; since there is no long-term commitment to the location, large camps of portable buildings are built instead. Even though the employees' days are almost entirely taken up by working and sleeping the supply of important basic amenities like energy is both important and costly. The provision of energy is particularly expensive as it often requires the transportation of large quantities of diesel over long distances. Even though Australian electricity prices are among the lowest in the world [1], a mining work camp of, e.g., 1,500 housing units spends more than $1.7 million a year on energy costs alone. Depending on the used fuel, such a camp accounts for emission of potentially more than 10,000 metric tons of carbon dioxide (CO_2) and contributes to the fact that Australia's greenhouse gas emissions per person are more than double the average, and thus the highest, of all industrialized countries [2].

While this should engender a responsible and effective use of energy in such a work camp, often the opposite is the case and excessive wastage is more the rule than the exception. The majority of residents program their air conditioning to keep their rooms cooled down to sometimes as little as 18 °C for the whole day just to make sure the room is nice cold when they come back from their hard work. While this is to some degree understandable – the temperatures in such regions often rise well beyond 40 °C – other negligence such as not turning off the TV when leaving for work cannot be explained as everything but ignorance and irresponsibility. The provision of strict guidelines to prevent such behavior and enforcement of those rules has proven to be very unpopular and to generate resentment among the residents. To overcome this problem automated strategies by which the required energy demand from each accommodation unit is intelligently minimized and any unnecessary waste is avoided are required. At the same time, it is important that the quality of living of the occupants is not reduced as this would diminish the acceptance of such a solution.

To address these challenges, we introduce a distributed system for ubiquitous monitoring of energy consumption and control of appliances through a new intelligent controller that dynamically manages the electricity usage of accommodation facilities in remote regions of Australia. This highly reconfigurable controller enables optimizations in energy consumption resulting in both, reduced ecological impact and energy costs. It dynamically manages appliances to reduce the overall energy consumption without reducing the quality of life of the residents. The system is built on a Web of Things architecture to leverage networking effects and to enable use cases beyond the pure reduction of power consumption. Apart from providing a standardized interface to the system based on

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widely proven technologies, this allows to leverage recent innovations in the field of Internet technologies. It is worth noting that, even though the system was tailored to remote working camps in Australia, it could as well be used in regular households around the globe with minimal modifications. However, we expect that the achievable savings in a regular household would be considerable lower since the residents pay their power bills directly. It is thus in their interest to avoid unnecessary wastage, in contrast to residents of the afore-mentioned accommodation facilities who have no direct incentive to do so.

The reminder of the paper is organized as follows. Section II gives an overview of related work which is followed by a discussion of the requirements and constraints that influenced the design decisions in section III. Then, section IV shows how we plan to enable serendipitous reuse by building the system in the form of a Web of Things and the advantages arising from doing so. After the system architecture and implementation are described in section V and VI, the results of a first field trial are analyzed in section VII. Finally, the concluding remarks and future work are presented in section VIII.

II. Related Work

Climate change, or global warming, is having an increasing and significant impact on everyone's lives. Shifting weather patterns resulting in increased incidents of extreme weather events such as floods, droughts, or extreme storms urge to action to prevent the worst impacts. After decades of controversial discussions, it is now widely recognized that global climate change is the result of a human-induced increase in greenhouse gas concentrations in the atmosphere. The burning of fossil fuel for the generation of energy in the form of electricity and heating for domestic, commercial and industrial use is by far the predominant source of greenhouse gas emissions worldwide [3]. Consequently, to decrease emissions, energy usage has to be reduced by improving efficiency and eliminating wastage.

Motivated by the need to modernize aging infrastructure, governments worldwide started to invest in smart grid technologies which cover both transmission and distribution grids. The main idea is to add intelligent controllers able to communicate with each other to every component from the power plant down to the consumer whereas traditionally intelligence was only applied locally by protection systems and by central control through supervisory control and data acquisition (SCADA) systems [4]. The increased connectivity, automation, and coordination between suppliers, networks, and consumers result in higher flexibility and efficiency. As a recent report from the U.S. Department of Energy's Pacific Northwest National Laboratory concludes, these investments can be further leveraged to reduce greenhouse gas emissions. The report states that a full deployment of smart grid technologies in the United States could decrease the annual energy usage and consequently reduce carbon dioxide emissions by twelve percent by 2030 [5]; this includes consumer energy savings of six percent attributed to feedback given by smart meters. The real- or near-time energy consumption data provided by smart meters and shown on in-home displays enables users to track down which appliance is causing a rise in energy consumption and thus to optimize their usage patterns [6]. Regardless of often being denoted as home energy management systems (HEMS) these systems effectively leave it to their users to take appropriate measures to reduce energy consumption as they do not control appliances directly but just monitor their power usage in order to generate statistical data. Nevertheless, it has been repeatedly shown that such feedback influences the energy consumption behavior of consumers and results in reductions in the order of five to ten percent [7]; whether users manage to sustain these initial savings over time is still being researched and the few available studies show indecisive results ([8], [9]).

Home automation technology offers a great potential to overcome this problem of home energy management systems as it could be used to reduce unnecessary energy wastage by controlling appliances directly. Given that resident behavior was often found to be the major contributor to the variance in domestic energy consumption [10], the achievable savings would likely be higher and the effect more enduring than purely relying on the willingness and willpower of residents to change their habits [11]. With rising energy costs and the community urging action on climate change, an increasing amount of research is being conducted to exploit the potential of combining home automation technologies and energy management systems to reduce power consumption.

All proposed systems have in common that they monitor energy consumption to predict and optimize future use. In [12] K.-M. Chao et al. focus on energy profiling of electrical appliances to detect abnormalities in energy consumption and recommend appropriate countermeasures. By creating household profiles they allow comparing a household's appliance's consumption to households with similar profiles, i.e., similar appliances. Other approaches go even further by trying to create user profiles. They typically use a (wireless) sensor network to monitor user behavior to create profiles that are subsequently used to predict user behavior in order to optimize the energy consumption by controlling home appliances in an automatic fashion. The differences in these proposals mostly rely in implementation details. The used techniques which range from algorithms based on fuzzy logic [13] and neural networks [14] to simple cross-correlation calculations [15].

Despite these promising efforts, adoption of home automation technology in general and its use in lowering energy consumption in specific has been very limited so far. Gill et al. [16] identified five problems that limit the consumer adoption, namely 1) complex and expensive system architectures, 2) intrusive installation which often requires physical wiring, 3) lack of network interoperability leading to "a complex maze of heterogeneous networks," 4) interface inflexibility, and 5) security and safety issues. Another fundamental factor for the low adoption is, in our opinion, the

lack of incentives to deploy such a system. Just providing an additional interface to control home appliances is not enough and, as described by Gill et al., the interfaces found in those products are more often than not too complex and too inflexible to satisfy their users.

III. Requirements & Constraints

Analyzing the related work and taking into consideration the underlying circumstances of our use case, we derived a set of requirements for the design of a distributed system to monitor and reduce energy consumption.

First of all, the system has to reuse as much as possible of the existing infrastructure to be cost-effective. This includes the existing network infrastructure as well as the used appliances. This makes it difficult or virtually impossible to automatically control some of the appliances as the necessary interfaces are not available. Nevertheless, in most brownfield projects it is not an option to require the replacement of appliances. In consequence, the system has to be built in a way to support as many different interfaces as possible. This also improves the extensibility of the system as it allows different types of appliances to be added at a later point in time.

A related requirement is the ease of installation as installation of home automation systems often considerably outweighs the system costs. This is partly due to the often required physical wiring which is both, expensive and inflexible, and partly due to the complex setup procedures to configure such a system. To mitigate those problems, existing wiring has to be reused as much as possible and when that is not possible, wireless communication should be considered instead. The setup routine should be simple enough to be completed without specialized training.

As mentioned before, the system should take advantage of the omnipresence of (already installed) home networks and Internet access. Consequently the architecture should be based on Internet technologies such as TCP/IP, HTTP and HTML. This not only allows to piggyback the system on the existing network infrastructure, but also to leverage already available clients such as PCs, smartphones, or tablets as an interface to the system. Since users are already familiar with those devices it makes sense to reuse them as an interface to the system instead of developing another, proprietary one which is potentially more complex and less flexible.

In addition to the abovementioned general requirements, we identified a set of specific requirements for the application of such a system in a remote accommodation facility in Australia. The major difference to a regular household is that the housing units in such accommodation facilities are targeted to a single person. Accordingly they have a living area of just 10-15 m² which usually consists of solely a bedroom with an en-suite bathroom. Therefore, major appliances such as stoves, microwave ovens, dishwashers, washing machines, or clothes dryers are missing in these accommodations. The hot water system is usually shared among a number of housing units to achieve higher efficiency and reduce costs. What remains is a small refrigerator, similar to those typically found in hotel rooms, an air conditioner, and a TV.

Laboratory measurements, estimates, and observations based on actual consumption data from remote accommodation facilities identified the air conditioning as, by far, the biggest energy consumer in such housing units. Information from independent facility operators suggested that it is also the source of most of the power wastage. It is thus an essential requirement to be able to intelligently control the air conditioning as this will provide the greatest benefit.

Due to the large number of housing units, all recorded data has to be transferred to a central server for further analysis as manual collection of the data is impractical. Where possible, data should be preprocessed on the node to minimize network usage. Unfortunately, the network infrastructure in such facilities has been found to be very unreliable. Hence, autonomous operation of system critical functionality must also be possible in the event of a network failure. Furthermore, all collected data has to be recorded locally until a connection to the central server can be established again.

An important aspect for the acceptance of the system is that it does not interfere with the resident's interests as the provision of strict guidelines to prevent energy wastage and their enforcement has already proven to be very unpopular and to generate resentment. Ideally, residents should not even be aware that the system takes control in their absence. Just as Mark Weiser stated [17] more than two twenty years ago, "the most profound technologies are those that disappear. They weave themselves into the fabric of everyday life until they are undistinguishable from it." Thus, minimal user interaction should be required and it has to be assured that the housing unit is at the same, or a very similar, state to when it was left by the resident. This usually means that the room should be cooled to a certain temperature when the resident returns from work.

From the system operator's point of view, important aspects include the ability to remotely control, configure, and update all system components. This lowers the total cost of ownership and improves the return of investment.

IV. Enabling Serendipitous Reuse

Allowing serendipitous reuse, in contrast to planned reuse, might sound contradictory because, by definition, serendipity cannot be planned. Nevertheless such serendipity is common on the Web and is most apparent in the form of mashups where previously unrelated services are combined to value-added services that often go beyond the scenarios that the developers of the underlying services had intended or even considered. As Steve Vinoski argues in his excellent article [18], platforms, although efficient for their target use case, often inhibit reuse and adaptation by creating highly specialized interfaces; even if they stick to industry standards. He argues that "the more specific a service interface [is], the less likely it is to be reused, serendipitously or otherwise, because the likelihood that an interface will fit what a client application requires shrinks as the interface's specificity increases." This observation surely

applies to most current home automation and energy management systems which consequently are rarely flexible enough to be used in unanticipated scenarios.

These issues can be solved by basing the system on an architectural style that encourages serendipitous reuse by providing a uniform interface. As has been shown countless times on the Web, REST [19] is one architectural style fulfilling these needs. A system based on such an architecture not only renders it possible to reuse existing infrastructure but also to solve the interoperability problems [16] of today's systems. Moreover, the exposed uniform interface allows devices to communicate with each other to coordinate their actions. In our use case this, e.g., allows to prevent spikes in power usage resulting from numerous devices being turned on at the same time. The fact that the whole Web, the largest and most successful distributed system, is built on REST's principles should be sufficient evidence of its superior scalability and interoperability.

By semantically describing the resources of the resulting Web of Things they can be integrated into the Linked Data cloud where they can easily be enhanced with additional data. Furthermore, this semantic annotation improves the evolvability of the system by allowing the creation of more flexible and dynamic clients that are able to "understand" or infer the meaning of the data they are processing. Forward compatibility, such as, e.g., adding a new sensor of a previously unknown type to the system, would thus be trivial since, e.g., a logging service would be able to understand that the new device is an instance of a sensor and that it has to record its reading; regardless of whether it understands the reading or not. SEREDASj [20], a semantic description language specifically designed for RESTful services, is one approach to achieve such flexibility. It creates complete descriptions of services and their exposed data that, as shown in previous work [21], can be used to create a generic and standardized data access API. This abstraction of the data access layer allows clients to be highly simplified by eliminating most of the usually needed data mediation code (which quite often accounts for the vast majority of the required client code). Consequently, most of the programming happens on a high level of abstraction. Since no complex low-level hardware knowledge is required, even average developers are able to maintain or extend the system as needed.

V. System Architecture

Based on the requirements described in the previous sections and considering the related work, we designed a Web of Things for ubiquitous monitoring of energy consumption and control of home appliances through an intelligent controller that dynamically optimizes power usage. The system architecture consists of intelligent nodes and smart meters connected to a central logging and control server as shown in Figure 1.

Every node consists of a controller and a number of sensors and actuators connected to it. Such a node as well as a smart meter is installed in every housing unit. The key aim of the

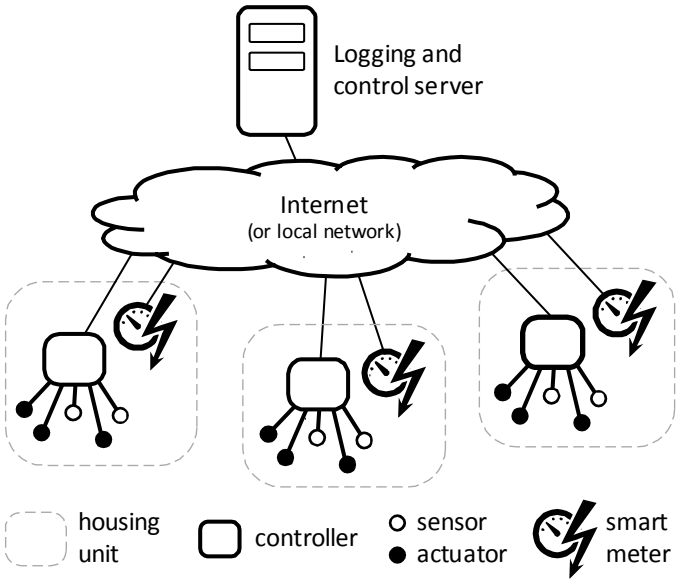

Figure 1. System architecture

controller is to automatically and proactively intervene in energy usage decisions with minimal or no manual intervention to drastically reduce the amount of energy wastage without affecting the amenity of the resident. The server is used to control and manage the whole system and to store the measurements of the sensors and smart meters in a centralized database for further analysis. In future, this data will help us to improve the algorithms to reduce the energy wastage. All the communication between the different system components is based on proven Internet protocols (mainly TCP/IP and HTTP) and implemented in the form of RESTful APIs. It is worth highlighting the every node acts as a HTTP client as well as a Web server. This results in a hybrid system in which some components form a peer-to-peer network instead of a network with clear distinction between clients and servers.

VI. System Implementation

As a proof of concept we implemented a first prototype of the described system capable to control and monitor off-the-shelf appliances. Given that the project resources were limited, the design of the controller was based on the Arduino platform [22], a popular open-source electronics prototyping platform. This allowed us to rapidly build a first running prototype without having to spend too many resources on building the hardware.

The chosen Arduino Mega features an Atmel AVR microcontroller and is programmed by in a C++ dialect. The board provides a wealth of well integrated inputs and outputs to control sensors and actuators. In total there are 54 digital input/output pins (of which 14 can be used as PWM outputs), 16 analog inputs and 4 UARTs (hardware serial ports). This and the available programming libraries gave us great flexibility and made it very simple to evaluate different sensors and actuators. To hook the controller up to the existing network in order to log the collected data to the central server we used an add-on board, called an extension shield, which provided

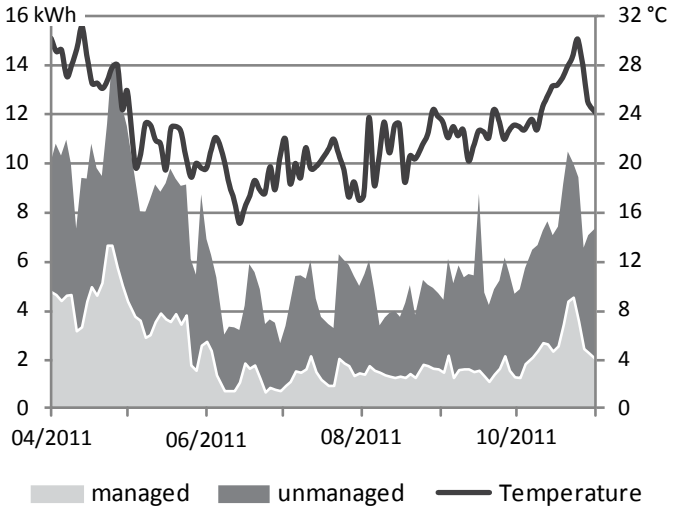

Figure 2. Absolute energy consumption of managed and unmanaged air conditioning

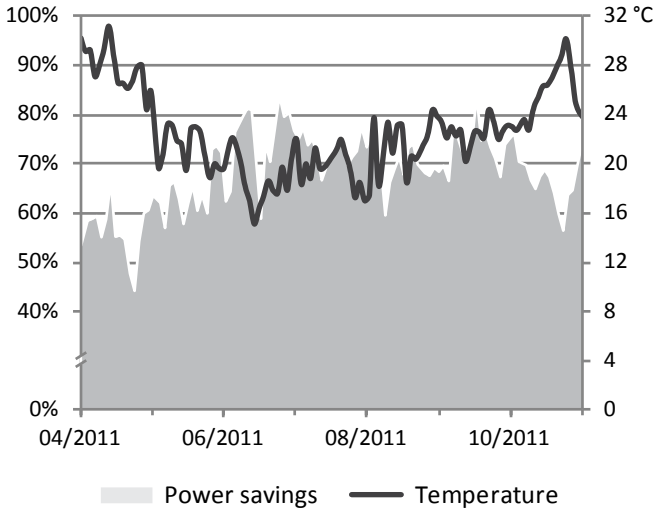

Figure 3. Power consumption savings of managed compared to unmanged air conditioning

Ethernet connectivity. The algorithms to monitor the environment and manage the air conditioning had to be kept as simple as possible since the hardware platform imposed severe constraints. It provides only 128 kB of flash memory, 8 kB of SRAM and 4 kB of EEPROM along with a 16 MHz clock speed and had to run the whole software stack which includes a complete networking stack.

A great amount of time was spent on connecting the controller prototype with the appliances to be controlled. As laboratory measurements and power consumption data suggested, the air conditioning was the most critical component in reducing the overall energy consumption. Unfortunately we were unable to interact directly with the air conditioner units as the manufacturers were reluctant to provide us with any information regarding the different hardware interfaces and it was unfeasible to replace the units. We thus had to reverse-engineer the infrared communication protocol and implement it on our controller so that it effectively emulated an infrared remote control. The advantages of using an infrared-based interface instead of a wired interface are simplified installation due to the reduced amount of required wiring and the fact that (almost) the same code can be used to control appliances from different manufacturers. With small modifications also completely different appliances such as TVs can be controlled.

To provide the management logic of the controller enough information about the environment it is controlling we used the following sensors: a passive infrared sensor, two temperature and humidity sensors (one of each is placed inside the accommodation and one of each on the outside), a couple of reed switches, and an RFID reader. The passive infrared sensor is used to detect motion which is then in turn used to infer presence. This is crucial since the accommodation should just be managed when the resident is absent. The reed switches are used to detect opening of doors and windows. If windows or doors to the outside are open longer than a certain amount of time, the air conditioning has to be turned off completely as it would not be effective and result in excessive power wastage. Finally, the RFID reader is used to enable keyless entry which, at the same time, allows collecting valuable information about who accesses an accommodation unit (the resident, cleaners, etc.). All the collected data is evaluated in real-time on the controller and additionally logged to the central server, which was implemented in PHP, for further offline analysis.

VII. Field Trial Evaluation

To evaluate the impact on the power consumption of the proposed system, we deployed the prototype described in the previous sections at a remote housing site consisting of more than 1,500 accommodation units in Karratha, Western Australia. In the form of a field trial we compared the energy usage of housing units that were controlled by our system to housing units that were purely managed by residents. The field trial was run for a period of seven months from April 2011 to November 2011. Due to the limited computing power of the controllers, the system was configured to control the air conditioning by a simple heuristic based on the roster of the resident instead of using more sophisticated algorithms. The air conditioning was set to 30 °C after the resident's work shift began and reset to 24 °C half an hour before the end of the resident's shift. This assured that the room was cooled down before the resident returned.

Analyzing the breakdown of the average power consumption of an unmanaged housing unit showed that roughly eighty percent of the whole power was consumed by the air conditioner, ten percent by the hot water system, and ten percent by other appliances such as lights, refrigerators, or TVs that were not directly instrumented. This is in line with our previous estimates and laboratory measurements that identified the air conditioning as, by far, the biggest energy consumer. The average power consumption of the air conditioning in a managed accommodation compared to the power consumption in an unmanaged accommodation unit is shown in Figure 2.

Even though the implemented strategies were quite simple, we were able to reduce the average daily power consumption of the air conditioning by more than sixty percent from 6.62 kWh to just 2.29 kWh per housing unit. This results in an overall energy consumption reduction of roughly fifty percent from 8.65 kWh down to 4.32 kWh per day. Facility wide, this potentially extrapolates to annual savings of 2.4 GWh corresponding to cost savings of more than $500 thousand and, depending on the used fuel, carbon dioxide (CO_2) emission reductions in the order of 1,000-2,900 metric tons. Two interesting aspects to note are that the savings are consistently greater than forty percent and that they grow as the ambient temperature decreases Figure 3. This stems from the fact that the housing units do not warm up as much and it thus requires less energy to bring the environment back to the target temperature before the resident returns.

VIII. Conclusions

Shifting weather patterns due to global warming are having an increasing and significant impact on everyone's lives. This global climate change is the result of a human-induced increase in greenhouse gas concentrations in the atmosphere whose predominant source is the burning of fossil fuel for the generation of energy in the form of electricity and heating. Consequently, to decrease emissions and prevent the worst impacts, energy usage has to be reduced by improving efficiency and eliminating wastage.

In this paper, we have introduced a distributed system for ubiquitous monitoring of energy consumption and control of appliances to reduce unnecessary power wastage. We have further presented the results of the first field which were highly significant. The fact that the field trial was carried out in a period of the year with relatively low temperatures surely affected the results to our benefit but, nevertheless, the achieved savings were substantial. This suggests that by using more sophisticated algorithms, savings in the same order could be achieved even on a yearly basis.

In future work we would like to improve the algorithms controlling the appliances. We are actively looking at approaches creating appliance and user profiles. Furthermore, we would like to explore the potentials offered by the semantic annotations of the services and the exchanged data. We believe that this not only will make the system more flexible, but also fosters serendipitous reuse in unanticipated ways. Since this requires more computing power, we have already commenced porting the system to a more sophisticated hardware platform running an operating system. This allows us to implement the system at a higher level of abstraction and to remotely update it; something that was previously impossible as the software had to be flashed to the hardware.

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