Augmenting Software Engineering Processes Towards Designing Privacy Aware Internet of Things Applications

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ABSTRACT
The design and development process for Internet of Things (IoT) applications is more complicated than for desktop, mobile, or web applications. IoT applications require both software and hardware to work together across multiple different types of nodes (e.g. micro-controllers, system-on-chips, mobile phones, miniaturised single-board computers, cloud platforms) with different capabilities under different conditions. IoT applications typically collect and analyse personal data that can be used to derive sensitive information about individuals. Without proper privacy protection in place, IoT applications could lead to serious privacy violations. Thus far, privacy concerns have not been explicitly considered in software engineering processes when designing and developing IoT applications, partly due to a lack of tools, technologies, and guidance. This paper presents a research vision that argues the importance of developing privacy aware IoT application design tool to address above mentioned challenges. This tool should not only transform IoT application designs into privacy aware application designs, but also validate and verify them. First, we outline how this proposed tool should work in practice and its core functionalities. Then, we identify research challenges and potential directions towards developing the proposed tool. We anticipate that this proposed tool will save many engineering hours which engineers would otherwise need to spend on developing privacy expertise and applying it. We also highlight the usefulness of this tool towards privacy education and privacy compliance.

CCS CONCEPTS
- Security and privacy → Usability in security and privacy; • Human-centered computing → Ubiquitous and mobile computing systems and tools; • Social and professional topics → Software engineering education; Computing / technology policy;

KEYWORDS
Internet of Things, Software Engineering, Usable Privacy, Tools

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1 PRIVACY CHALLENGE AT DESIGN TIME
The engineering complexities in Internet of Things (IoT) have forced engineers to focus most of their efforts on addressing challenges such as interoperability, reliability, and modifiability, resulting in privacy concerns being largely overlooked [5] [7]. IoT applications typically collect and analyse personal data that can be used to derive sensitive information about individuals. Without proper privacy protection in place, IoT applications could lead to serious privacy violations. Over the last few years, we have seen number of privacy violations (e.g., Baby monitor [14], Google smart speaker eavesdropping [3]).

Traditionally, privacy challenges are addressed in an isolated manner by different research communities (e.g. networking, database, software engineering, human computer interaction) [5]. More importantly, such independently developed solutions are complicated to adopt and require significant expert knowledge, time, and resources. In contrast, we propose an end-to-end unified technique that does not require expert knowledge in order for it to be adopted, therefore reducing the cost associated with designing privacy aware IoT applications. Our vision is to develop a tool that the software engineering community has not seen before that would not only bring privacy-by-design (PbD) into mainstream engineering but also ensures that IoT applications are compliant with leading laws and regulations (e.g. General Data Protection Regulation (GDPR) [6]) working towards creating a safer and privacy aware IoT ecosystem. Usability, consistency, trustworthiness, scalability, accuracy, accessibility, and extendibility are major unique characteristics of this tool.

1.1 A walking Through Example
Let us consider a simplified use case scenario to highlight the challenges in designing privacy aware IoT applications. A doctor needs an IoT application which can be used to monitor patients’ rehabilitation process. This use case is inspired by a real world application called ‘MyPhysioapp’ (myphysioapp.com) [4]. Doctor has compiled his functional requirements as follows. The doctor has difficulties in seeing his patients frequently due to different reasons (e.g., travelling distance, work schedules, etc.). Further, frequent in-person consultations are not necessary in most circumstances. Each in-person visit costs for both doctor (government) and the patient. Once the initial consultation is performed, doctor only needs to track the patients progress and does not need to meet patient unless there is something exceptional happened. The doctor is only interested in tracking the patients progress. After evaluating the progress every two weeks, doctor may ask his speciality nurse to change the exercise plan as necessary.

Two software engineers have come up with two different designs as follows to fulfil the above functional requirements. The designs are visually illustrated in Figure 1.

Design 1: In this design, wearable sensors are used to capture raw data (e.g., accelerometers, gyroscopes) that can be used to identify users’ (patients) activities. Data is then sent to the
cloud for activity recognition using a mobile phone as an intermediary device. Next, the cloud services are used to process the raw data and in order to identify the users activity patterns. User activity patterns are then compared with doctors recommended rehabilitation plan to produce a progress report. The doctor can review the progress and make recommendations to the nurse regarding any alterations.

**Design 2:** In this design, wearable sensors are not only used to capture raw data but also to identify activities (using the micro-controllers attached to the wearable). Timestamped activities are then sent to the mobile phone. The nurse, based on the doctors’ recommendations, creates the exercise plan and send to the patient’s mobile phone. The mobile phone then compares the timestamped activity data and the exercise plan in order to determine how well the patient is performing the exercises. The mobile phone sends a weekly progress report to the doctor. Based on the report, doctor gives advice to the nurse and she alters the exercise plan accordingly.

It is important to note that both designs satisfy doctor’s functional requirements. However, design 2 is certainly ‘better’ than design 1 in terms of privacy awareness. Based on this use case scenario, we extract two research questions as follows:

- How can we define and operationalise ‘better’ IoT application designs (in terms of privacy)?
- How can we automatically convert a ‘weaker’ designs (e.g., design 1) into a ‘better’ design (e.g., design 2).

We consider privacy as a trade off function. Applying a certain privacy preserving measure into a certain IoT application may impact the implementations in terms of costs, complexity, usability, fault tolerance, responsiveness, etc. Therefore, our aim is not to prescribe a certain design over other. Instead, we want the developer to be informed about privacy-by-design choices before they make their final design decisions. In this regard, we propose a usable privacy aware IoT application design tool which will inform the privacy aware design choices to the developers. Previous investigations have shown that applying privacy principles into IoT applications is time consuming and difficult [12].

### 1.2 Target Roles and Audience

We believe such a tool can be beneficial to different types of stakeholders as follows:

- **Design Tool for Software Engineers** (designers / architects): Primary stakeholders of this tool would be software engineers. We expect them to use this tool to sketch their potential IoT application designs and get validated before moving to the implementation phase. This tool will provide different types of suggestions which engineers can use to improve their IoT application designs in terms of privacy. More importantly, we do not expect this tool to act as black box that just spit-out application designs. Instead, each recommendation will be justified by the tool so engineers can understand why the tool is making a certain recommendation.

- **Compliance Tool**: This tool will also be useful to demonstrate certain compliance needs (e.g., GDPR [6]). It will have the capability to automatically generate a compliance report for each IoT application design briefly explaining the design decisions and risks associated with, so the compliance officers can determine whether to approve or not. We envision that, in the future, such compliance tool could be useful (or may be required) when submitting an IoT application to IoT app stores.

- **Education and Awareness Tool**: We also expect this tool to be used for enhancing privacy awareness among students from school level to university level. Over the last few years, there have been many program environments and languages been developed to help young children to learn how to code (tynker.com, scratch.mit.edu). Similarly, we believe that everyone should learn about privacy at their young age so over time they will become responsible software engineers who care about privacy. Privacy Mindset [12] is really important to be developed by software engineers.

### 2 TOOL ASSISTED PRIVACY AWARE IOT APPLICATIONS DESIGN

The tool we propose is something that the engineering community have not seen before. However, it is inspired by many existing tools used by the engineering community (e.g., UML design tools). First, let us illustrates how the proposed tool (and underline technology) is expected to work in practice using Figure 2.

(Step 1) Software engineers will draw their application designs using pre-defined set of notations. Key components will be nodes (device profiles) and data flows. To ease the process, common device profiles will be provided. This process will look like a UML diagram design process. (Step 2) Engineers will then specify the service which they plan to run. (Step 3) They can either assign each service to a node or just leave them unassigned for the algorithms to do that in a later step. (Step 4/5) Optionally, engineers can provide additional information related to data management (e.g., 90 days data retention) and context (e.g. healthcare domain). Additional
information will help the algorithms to better design IoT applications. The rest of the steps are invisible to engineers and triggered by a single click. (Step 6) Algorithms automatically assign each service into nodes appropriately by considering device capabilities, runtime requirements of the services, and other relevant context information. (Step 7) Algorithms incorporate privacy protection features into the design. This step may also reallocate the services into different nodes, if necessary. This is one of the key features of this tool. (Step 8) Algorithms examine the privacy awareness at both node and composition levels. Then, all the results will be combined to produce the overall privacy index and presented to the engineers. Engineers may consider changing their initial designs to improve the privacy index. (Step 9) The terms and conditions unique for each IoT application design are automatically generated.

So far we designed the IoT application assuming the target environment is static. This works sufficiently for use cases like above. However, some types of applications would require adaptation at runtime to better serve the users. In reality, IoT environments are highly dynamic in nature. Therefore, IoT applications should be able to adapt at runtime. Towards this direction, we believe this tool should provide simulation capabilities so the engineers can evaluate how their application might adapt at runtime under different circumstances. We discuss adaptation in Section 3.3.

3 RESEARCH DIRECTIONS

3.1 Design Notations and User Interactions

We envision this tool to follow the visual programming paradigm [15]. The proposed tool is expected to be used by engineers to design IoT application by manipulating program elements graphically. We expect such design process would be natural for engineers as they are typically familiar with design approach such as Unified Modelling Language (UML) and Data Flow Diagrams (DFD). Such familiarity will help engineers to quickly familiarize themselves with the tool. Ideally, the visual programming language will be inspired by the data flow diagrams notation. A data flow diagram is a graphical representation of the ‘flow’ of data through a system (in this case IoT system), modelling its process aspects. However, it is important to note that DFDs are flexible enough to be represented in different levels of complexities. Therefore, it would be a fine balance between maintaining the simplicity while allowing engineers to design their systems in detail. In addition to the DFD based information, the tool should have ways to gather other related contextual information. Tool should show errors / warnings when vital pieces of information are not provided by the engineers (e.g., data retention period). Knowledge-bases can be used to provide assistance and recommendations for the engineers (typical data retention period based on the domain, data types, applicable laws, and so on) [13].

3.2 Privacy Patterns and Knowledge Modelling

Incorporating privacy preserving techniques into IoT applications is a complex and time consuming process [12]. Traditionally, in software engineering, such complexities are handled through introducing design patterns. Design patterns are general repeatable solutions to commonly occurring problems. Design patterns can also speed up the design and development process by providing tested and proven solutions. We believe that this tool should be knowledge driven. This means that algorithms should not require constant upgrades while the knowledge-bases will grow overtime enabling new features and capabilities. To achieve this, we propose to create a privacy patterns library (by both developing new privacy patterns and organizing existing privacy patterns [11]). Ontology based knowledge models can be developed in order to model the information about each privacy pattern in a common structure. Such common structure and semantic interoperability allows algorithms to manipulate patterns in semantically meaningful way. Pattern candidate need to be extensively analysed to find out their characteristics (e.g. usability, complexity, abstractness, relationship to other patterns, composability) and to categorise them from different perspectives (e.g. functionality, level of granularity). Such analysis would be vital in the next phase.
3.3 Context Aware Planning and Adaptation

The design and development of IoT applications require both software and hardware to work together across multiple different types of nodes (e.g., micro-controllers, system-on-chips, mobile phones, miniaturized single-board computers, cloud platforms) with different capabilities under different conditions (e.g., CPU, memory, energy, data communication, knowledge availability, energy limitations, latency tolerance limitations, domain requirements). Therefore, the privacy preserving techniques that can be applied on a given node varies depending on the context. The question that needs to be answered is "How do we optimally allocate responsibilities to each node based on the context when designing a privacy aware IoT application?"

First, we need a knowledge base that can be used reason about different IoT application design choices. Secondly, we need algorithms that can decide which privacy patterns to be used in different nodes individually and as a whole. Towards this, techniques developed by web service composition community would be useful. This challenge could be addressed by formulating it as a service composition (with constraints) problem [10].

The IoT ecosystem is highly dynamic in nature. Therefore, IoT applications should be able to adapt to the context changes at run time. However, it is difficult to predict how such adaptation would work at runtime. We believe that the proposed tool should be able to provide engineers with some insights on how their applications would adapt. Let us consider a home care example scenario. Assume three IoT systems are deployed in a home as follows: 1) care receiver wears a smart band that tracks health; 2) a smart bed that can adjust its height, 3) a smart carpet that tracks movements. Assume that none of these IoT systems are originally designed to detect fall and notify caregivers. For example, a novel IoT application may be originally developed to detect fall by using smart band data. The challenge is, how such an IoT application should behave, if the smart band fails (e.g., hardware failure)? Can the IoT application adapt and reconfigure itself based on context? (e.g., IoT application reconfigures itself to re-utilize data from smart bed and smart carpet to detect fall, instead of the failed wrist band). As the IoT application changes at runtime, privacy protecting measures may also need to change accordingly to support the adaptation. The tool should be able to simulate scenarios in order to evaluate the quality of the application design as well as its adaptability.

3.4 Operationalisation, Measuring and Rating

Finally, the challenge is how engineers know, given an IoT application design, whether it is a good design or a bad design (from privacy perspective). We tend to understand different types of measuring and rating / indexing techniques well (e.g. Body Mass Index, energy ratings, food reference intake and so on). However, no such mechanism is available to measure privacy awareness of IoT applications. We believe such mechanisms (e.g., privacy index) would be increasingly important for both engineers and end users. Engineers can use such index to evaluate their own applications to iteratively improving their designs. End users can use such index to understand how each IoT application manage their data. Operationalisation of privacy is a challenging task. There are many factors to take into account when generating an privacy index for a particular application design. Some of the major factors are: 1) privacy patterns used (individually and compositions), 2) order of privacy patterns applied, 3) sensitivity of the data involved, 4) potential risks, and so on. After Operationalising, these factors need to be combined together in a meaningful way. Crowdsourcing techniques [11] may be used to combined expert knowledge and end user expectations to generate a privacy index.

Another challenge that goes hand in hand with rating is Terms and Conditions (T&C). It is a well-known fact that end users hardly ever read T&C [2, 9] related to any product or service, besides IoT applications. Typically, T&C are written as piles of text and therefore difficult to understand the most important information within the end users’ short interest and attention span. From engineers’ point of view, putting together a T&C document is also a time-consuming task that requires lot of effort and specialist expertise (e.g., legal professionals) and also less trust worthy (due to human involvement). We propose to capture and model privacy expert knowledge using knowledge-based AI techniques, so the algorithms can eliminate the necessity for privacy experts and related human errors. Such knowledge could be used to automatically generate the (T&C) based on the design of the IoT application.

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