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TigerAware: An Innovative Mobile Survey and Sensor Data Collection and Analytics System

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***Abstract*—From health to community assessment, mobile phones have become a cornerstone of data collection across many areas of research. However, mobile phone-based studies are difficult to develop and deploy, often requiring in house development teams and large portions of research budgets. In this paper, an innovative system called TigerAware is presented to address this issue. TigerAware is developed to offer a generic and customizable tool, which allows researchers to create surveys to collect a wide range of data, including but not limited to question responses, on device sensor data, such as GPS data, and external sensor data, such as blood alcohol level from a Bluetooth breathalyzer. TigerAware is highly modular and uses advanced Web and mobile technologies to incorporate diverse data sources with a rich set of survey question types, requiring little development work by researchers for their individualized studies. TigerAware has been applied to a focus group and several pilot studies and shown excellent capabilities to be easily adapted and deployed for new types of data collection and analytics tasks and a wide range of research fields.**

***Index Terms*—mobile survey creation, mobile sensing, customizable survey and data collection, data analytics, ambulatory assessment**

I. Introduction

Researchers in different fields continuously search for ways to gather novel, insightful data to draw more robust conclusions. Over the past decade, this search has led researchers to rely heavily on the most ubiquitous device available—the smart phone. Smart phones have quickly become predominant in the United States, with 77% of Americans owning smartphones nowadays, up from just 35% in 2011 [16]. Smart phones are even more predominant in younger populations, with 92% of Americans aged 18- to 29-year-olds owning one [16]. Smart phones are cheap and an easy way to collect information without a major learning curve. Modern devices also come equipped with a wide array of specialized sensors including an ambient light sensor, GPS, proximity sensor, accelerometer, digital compass, microphone, and camera. Researchers can use each of these data sources to explore new scientific questions.

Yet using these devices in a research context does pose a significant challenge as the unique needs of each study requires custom software and a dedicated development team. For example, a medical researcher may need to collect answers to one set of questions at certain time intervals and be notified when a patient enters an actionable survey response. A psychologist may need to collect answers to another set of questions and also the ambient light data. Once data is collected, researchers may also need to visualize and interact with data in different ways. The software development to accommodate these needs is costly and time consuming, diverting resources from the research process. To greatly reduce the software development and budgetary restrictions and provide more flexibility and capability for researchers conducting smart-phone-based research, we developed TigerAware, a multi-tenanted platform for researchers to easily author, deploy, and manage survey and sensor-data based studies.

TigerAware can be easily incorporated into a field study with little modifications to the existing work flow and reduces the necessity of allocating significant funds for development of the IT system. Furthermore, the platform is highly configurable, allowing researchers to integrate novel data sources and interfaces. As an example, we recently integrated a blood alcohol level data type and and voice based assistant interface with minimal effort.

TigerAware has significant advantages over previous commercial and academic research data collection platforms. By including existing state-of-the-art features and considering various sensors used in a range of existing research studies, we were able to greatly improve upon existing platforms. In addition, data collected from the sensors and survey responses can be visualized on TigerAware's dashboard in real time. As a result, TigerAware is developed to offer a generic, customizable survey creation, deployment, and survey data and sensor data collection capability for researchers who want to use mobilephone-based surveys in conjunction with various internal or external data sources, including wireless and wearable sensors and Internet of Things (IoT) devices. TigerAware is highly modular and uses advanced web and mobile technologies to incorporate diverse data sources with a rich set of survey question types, requireing little development work by researchers for their studies. TigerAware has been applied to a focus group and several pilot studies and shown excellent capabilities to be easily adapted and deployed for new types of data collection tasks and a wide range of studies.

Overall, contributions of this work include a powerful new

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survey creation and data collection tool for a broad range of field research; a set of general and easy to use survey development tools for iOS, Android, and web development; a simple yet powerful cross platform protocol for IoT communication; and a means of rapid cross platform mobile survey development.

II. Related Works

As smart phones have become ubiquitous, they have allowed for novel methods of investigating a broad array of fields ranging from social science, to psychological science, to clinical research. Examples include ecological momentary assessment (EMA) for psychological studies [10], [18], [20], clinical assessment and self-management [7], and remote monitoring [13]. Though each of these domains focuses on different research questions, they have common technical components that often include:

1) Recurring data input by a user on a mobile device, such as providing answers to survey questions.
2) Collecting data from a mobile device's internal sensors or external wirelessly connected sensors.
3) Manageing multiple participants and their data across time.
4) Visualizing and analyzing collected data on a Web dashboard.

Several previously developed cross-platform systems provide these components in the context of a specific research question. For instance, Psychlog is a mobile platform designed to monitor participants' mental states, and collects users' psychological, physiological, and activity information [8]. Psychlog also allows users to enter self-report data so changes in mental state can be tracked over time. Psychlog offers advanced physiological data collection capabilities, including a real-time readout of ECG and accelerometer data on a mobile phones screen. However, Psychlog lacks a cross-platform study management capability and is limited to psychology applications, whereas TigerAware supports customizable questions and advanced study management across fields.

REDCap is a clinical research tool developed by Vanderbilt University that can be used to author, deploy, and analyze a wide array of clinical studies [9]. As with TigerAware, REDCap also uses a metadata-driven method of survey creation and deployment, but is limited primarily to a medical context. REDCap allows for creation of projects backed by a SQL data store including five predefined tables such as metadata, logging, and regular data. This is different from a NoSQL store employed in our methodology in that SQL is more restrictive of the field types that can be entered, limiting the research contexts the platform can be deployed in.

AndWellness is another wellbeing centered platform focusing on data collection using mobile phone's for the purpose of self-monitoring [11]. AndWellness offers an advanced suite of study management tools, including mobile phone and dashboard components. AndWellness also supports research across different fields, but does not come with a builder module; thus it requires programmer assistance for each new study.

Several other mobile monitoring platforms have also been developed which allow users to author new studies. From systems enabling epidemiologists to view changing conditions throughout a community [3] to platforms monitoring community atmosphere and noise levels [12], generic surveys have also become pivotal to community monitoring efforts.

Some recently developed systems aim to synthesize device data, survey responses, and physiological data obtained from third party devices. DEMONS is an integrated framework for synthesizing active and passive data sources using smart phone data and a wearable sensor [6]. Similar to TigerAware, DEMONS offers a generic authoring framework for new studies. DEMONS allows researchers to author new surveys including physiological data without any programming necessary; however, DEMONS restricts researchers to using only one external device (Basis Peak fitness tracking watch). TigerAware offers the capability to extend to new external data sources, such as a wearable chest sensor being used in conjunction with mobile surveys to better understand mood dysregulation [19] and alcohol consumption [21]. Other work has incorporated device data and sensor data to evaluate how each can contribute to mobile health (mHealth) applications [15]. In each of these scenarios, survey data is combined with independent data sources collected from a mobile phone sensor, or an externally connected device (i.e. Bluetooth wearable).

Different from existing systems, TigerAware aims to offer an overarching tool for authoring mobile surveys across disciplines and provide flexible and strong support for integrating new data sources, wireless sensors, and IoT devices.

III. TigerAware System Design and Implementation

A. Survey Grammar

A core element of TigerAware is customizable mobile survey creation. Data collection in a research study is formulated as the responses to survey questions on a mobile device over time. Each survey is composed of a series of questions. Table I shows the survey grammar, the rules for constructing surveys. A survey is composed of a sequence of steps, of a standard step type or a conditional step type. Figure 1 shows an example of the conditional-step where the next survey question to be displayed depends on the answer to the current question. Steps are combined to form a survey blueprint and a combination of these steps can create any type of survey.

B. System Architecture

TigerAware embraces a modular and generic system design to enable cross platform capabilities as well as rapid development of new functionalities. TigerAware consists of two major components: a central database and interpreters, as shown in Figure 2.

1) Central Database: TigerAware's central database is a NoSQL database consisting of three key parts: a blueprint store, a response data store, and a user store.

TABLE I
TIGERAWARE SURVEY GRAMMAR THAT DEFINES SURVEY SYNTAX.

Attribute	*Rule*
survey	[steps]
steps	conditional-step step step, steps conditional-step, steps
conditional-step	{ conditional-step-attributes }
conditional-step-attributes	conditional-pairs conditional-pairs, conditional-step
conditional-pairs	”title”: string ”id”: string ”subtitle”: string ”type”: conditional-types ”choices”: choices-value ”conditions”: conditions-value ”conditionalDefault”: string
choices-value	[string] null
conditions-value	[condition] null
conditional-types	”BAC” ”ContinuousScale” ”MulitpleChoice” ”Scale” ”YesNo”
condition	{ ”trigger”: value, ”toID” : string } { ”trigger”: value, ”toID” : string }, condition
step	{ step-attributes }
step-attributes	step-pairs step-pairs, step-attributes
step-pairs	”title”: string ”id”: string ”subtitle”: string ”type”: type-values ”conditionalDefault”: string
type-values	”TimeInt” ”TextFeild” ”TextSlide”

```
conditional-step = {
    "id": "q1",
    "title": "Are you above 18 years of age?",
    "subtitle": "",
    "type": "YesNo",
    "choices": null,
    "conditions": [
      {
        "trigger": "Yes",
        "toID": "q3"
      },
      {
        "trigger": "No",
        "toID": "q4"
      }
    ],
    "conditionalDefault": "q2"
}
```

Fig. 1. An example of the conditional step in TigerAware survey.

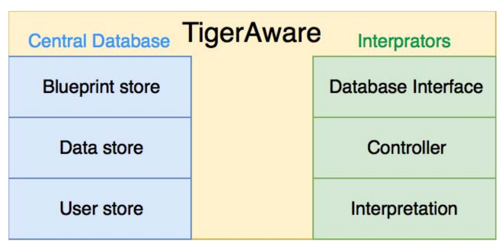

Fig. 2. TigerAware consists of two major components: central database and interpreters.

The blueprint store holds instructions to define TigerAware survey or data collection modules, as illustrated in Figure 3. Survey instructions are comprised of information such as the survey name and instructions to make each step in the survey (survey blueprint). Each step in a survey could be a text slide, which delineates a section of a survey, or a point of input like a ”yes” or ”no” question. Each step is kept as its own unit to allow the interpreter to decide whether it wants to combine the steps into a single interface or separate interfaces. Each step may include additional configuration metadata, but all steps must include at least a unique id for identification and a type to define the behavior of the question. All parts of survey instructions, including the survey steps, are left generic to enable different interpretations of questions. Despite the genericness of the survey, all the information necessary to define the steps is conveyed in the instruction. Researchers

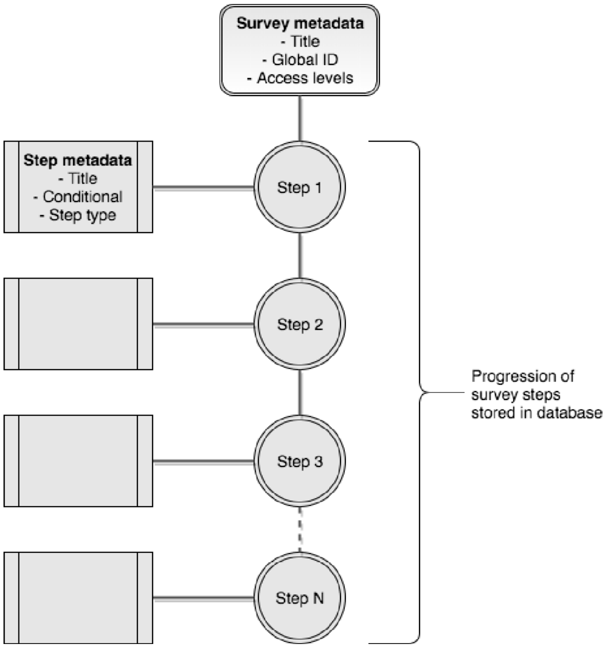

Fig. 3. The survey blueprint structure in TigerAware.

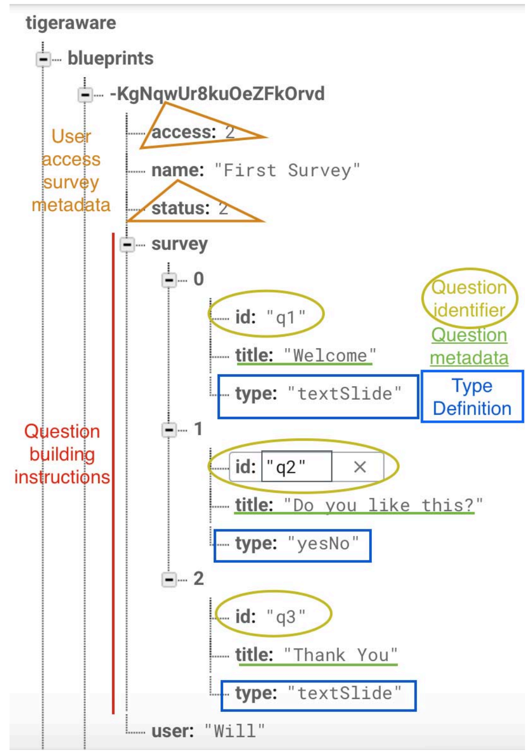

Fig. 4. A sample blueprint definition.

can add new step types by conforming to the step type interface. These step types could be traditional survey types, such as multiple choice or Likert scale, or more advanced types, such as physiological or device data (e.g., that from a wireless breathalyzer device). Figure 4 shows a sample blueprint definition. Table II lists the major step types in TigerAware.

The second main component of the database is the response data store containing survey data captured from mobile devices. The storage of response data alongside the corresponding blueprint data is important because the blueprint data enables interpretation of the survey data.

Finally, the user store contains user information, separately from the blueprint and response data stores. If desired, these database parts can be stored in three distinct databases to ensure privacy for users, improve scalability, or isolate data pertinent to different use cases. In this way, the three stores function independently of one another to enable more modularity and functionality.

A NoSQL database was used because of its high levels of modularity and genericness. One impediment we encountered when trying to develop TigerAware using a SQL database was that each survey required a different schema since each step corresponds to a different column in a SQL style store. Moreover, we use Firebase as our NoSQL data store because it decreased development and deployment time. The process of creating a new Firebase database and connecting it to a new platform takes just a few minutes. Because the database is structured from the frontend interpretive nodes, after a Firebase database has been created and connected to the nodes, backend development is essentially complete. An added benefit is that Firebase can also be used on a large number of diverse platforms, including mobile and the web.

2) Interpreters: TigerAware's interpreters are comprised of three key parts: database interface, controller, and interpretation.

The database interface reads or writes parts of the Firebase. An interpreter can read from or write to any of the three segments of the database. Because of the high level of modularity in the Firebase, the database interface part of interpreters are consequentially highly modular and generic as well.

The second part of interpreters is the controller, which takes what has been read and builds TigerAware surveys or survey related entities. The controller is modular and generic because of the high levels of modularity and genericness in both the interpretation and database interface parts. Modularity and genericness is also essential in the controller to maximize reusability. For example, although TigerAware's iOS app launches a survey when a user taps a survey's table view cell, a survey could be launched based on any action like a button press or a rotation of phone.

The final part of interpreters is interpretation. In iOS, ResearchKit is primarily used as the interpretation part. ResearchKit is an SDK for rapid modular development of surveys. If the controller calls for a yes or no question, the interpretation part converts its call to ResearchKit instructions to produce a yes or no question and adds it to a survey. Once a survey is produced, the controller enables a user to take it at any time. Once a user takes a survey, ResearchKit

TABLE II
MAJOR STEP TYPES IN TIGERAWARE.

Step Type	Description	Configuration
Text Slide	Give instructions to the user and separate segments of questions.	• Next question label
Text Field	Allow users to enter a free form response.	
Multiple Choice	Allow users to select one of a series of options. Can also be configured to select multiple options.	• Each multiple choice question option • Question to branch to if selected • Enable multiple selections
YesNo	A subset of multiple choice only allowing for yes and no responses.	• Question to branch to if selected
Date & Time	Prompt users to select a date and time an event occurred or will occur.	• Select both date and time • Select dates prior to current date • Select multiple dates
Time of Day	Prompt users to enter a time.	
Scale	Allow users to select a value from a scalar row of options.	• Number of intervals • A label for each interval value
Numeric	Prompt users to enter an integer value from a configured range.	• Minimum integer value • Maximum integer value
BACTrack Alcohol Sensor	Collect user blood alcohol level from BACTrack breathalyser.	• Display BAC to user

produces a result. The controller receives the result and passes it to the database interface, which stores it in the Firebase. ResearchKit thus provides a modular protocol for interpreting survey instructions and producing survey data from those instructions. ResearchStack was used in place of ResearchKit on Android, and the TigerAware team has developed replacements for ResearchKit on platforms that have no substitutes, such as the Google Home smart speaker.

Figure 5 shows an overview of TigerAware system architecture and interactions between components.

C. Benefits

1) Broad Usability: TigerAware's genericness and modularity yield cross platform capabilities. Because TigerAware's components and instructions are contained and generic, they can be interpreted in different ways. TigerAware's interpreters can be categorized into 3 main categories: readers, writers, and analyzers. An example of a reader would be an iOS device, an Android device, or a Google Home because they read instruction data to build surveys. An example of a writer is a survey-authoring Web dashboard that produces survey instructions from user input. An analyzer would read, analyze, and write both blueprint and survey data. An example of an analyzer is a server that processes images of fish and determine their species and length, or a server that takes in mood and physiological data and predicts when users would experience what mood. Readers have been developed on iOS, Android, and Google Home, whereas writers have been developed on iOS, Android, and Web. This cross platform nature is possible because of Firebase's accessibility by many platforms as well as the genericness of the instructions.

2) Reusability: TigerAware's genericness greatly enhances cross-platform capabilities and its modularity produces rapid development. The interpreters' controller part is essentially a layer of abstraction on top of its interpretation part like ResearchKit. This control layer creates within interpreters a set of reusable parts. If developers need to access any part of the interpreter or the database, the control layer enables them to do so. For example, in the iOS implementation, if a user needs to input any data anywhere in the app, a developer can build that input, present it, and gather its data with very few lines of codes. Firebase itself is also highly modular and reusable due to its easy set up process and front-end database management. New Firebase databases can often be created, connected, and deployable in a few minutes. Additionally, Firebase's model creation is accomplished entirely from front-ends. Firebase's front-end database management enables developers to simply connect their Firebase to a TigerAware interpreter and then the interpreter will build all parts of a database that it needs to access. This high level of modularity effectively eliminates the need for backend development given existing interpreters. Eliminating the need for backend development dramatically enhances the development process. Developers of new platforms need only conform to TigerAware's protocol and connect to a Firebase. TigerAware has been refactored into several different forms on iOS very quickly. TigerAware for iOS was been adapted into a diabetes research app within a 2-week period and a demo scavenger hunting game app within

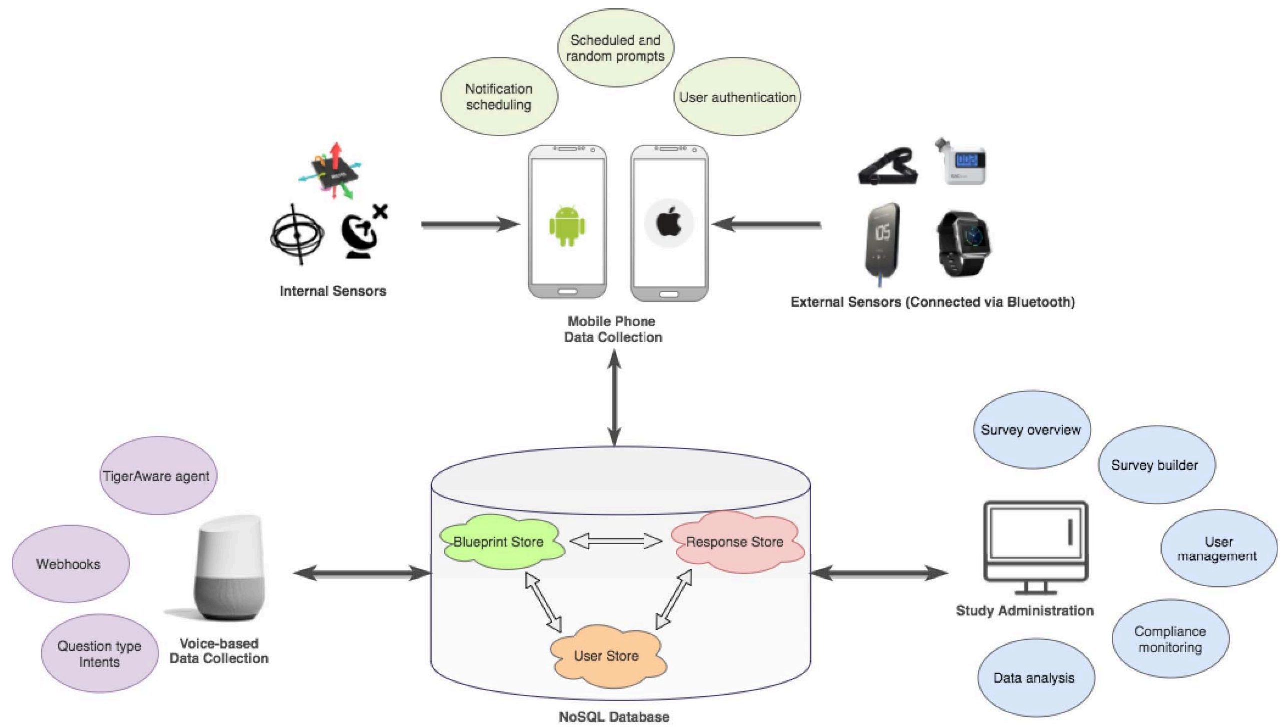

Fig. 5. TigerAware system architecture and components.

a 2-hour period.

D. Mobile Platform Support

TigerAware has been developed on both Android and iOS. Both platforms closely conform to the aforementioned system architecture. Both platforms use their respective Firebase APIs as their database interface. Additionally, each have custom-made controllers with the iOS version being developed in Swift and the Android version being developed in Java. For interpretation of rules into surveys, iOS uses ResearchKit [1] and Android uses ResearchStack [2], each of which are open source projects for rapid research development. ResearchKit and ResearchStack both support many of TigerAware's question types such as yes or no questions, multiple choice questions, and scale questions. We made slight modifications to both open source projects to add new data sources, such as a breathalyzer question type. The breathalyzer question type uses the BACtrack breathalyzer to collect blood alcohol content data. The mobile platforms also support complex question branching during a survey with default and triggered branching behaviors, meaning a user can trigger a branch based on a question response. Both platforms support survey creation and customization for researchers through a Web dashboard.

E. Voice Conversation Module

To support the deployment of surveys to a voice based digital assistant, such as Google Home, a voice conversation module is developed to convert the surveys stored in Firebase into a voice conversation, where the questions will be spoken and the user answers each question by voice. DialogFlow, a human-computer interaction technology based on Natural Language, was used. The conversation module consists of four major parts.

1) Voice Agent. The voice agent is a natural language understanding module that converts user voice responses into text and actionable data.
2) Question type Intents. Intents are the backbone of the conversation module. They recognize what the user is saying and what action should be taken by the webhook.
3) Expected Response Based Entities. These entities are used to extract a parameter values from natural language inputs. Entities are designed based on the expected response from a question type. For example, the expected response for a question like *"Are you over 18 years of age?"* would have an expected response of *Yes or No*. Hence, the entities defined for an intent handling *Yes or No* question type would use Yes and No as entity values. DialogFlow supports system, developer and user entities. TigerAware uses a combination of system and user specific entities to provide users the ability to respond in a natural way.
4) Webhook. DialogFlow provides a linear flow of questions and answers, and creates responses to user inputs. To provide richer sets of responses and conditional elements, a webhook (REST API) using Node.js and the express node package is created. JSON responses from

the DialogFlow agent containing processed parameters of the natural language input by the use is used to develop execution logic based on application requirements. The webhook also uses TigerAware's oAuth2.0 endpoint to authenticate the user and provide an *access token* that helps the webhook connect with Firebase to retrieve user specific surveys and store the responses from each user.

F. Web Dashboard

TigerAware's dashboard plays a vital role in the work flow of research studies and was designed to allow researchers to easily deploy different types of studies. Through it, users can create surveys or import surveys, perform user management, and visualize results in real-time. The dashboard was developed using AngularJs, an open source JavaScript based front-end application framework for single page applications. This allows us to follow MVC architecture in the development of our dashboard which breaks down each feature into its own separate module, making development, maintenance and future additions into the platform more manageable. Currently, the web dashboard consists of the following modules.

1) Survey Overview Module: The module provides administrators an overview of their current surveys (i.e, a high level understanding of the project showing them the number of responses collected, and the state of deployment). It also allows administrators to disable the surveys from appearing on the user list, thus allowing administrators to test a survey before deploying it to the users.

2) Survey Builder Module: Survey administrators can create a new survey using the survey builder. The user interface was carefully designed to be intuitive. The survey builder supports various question types like yes-no, multiple choice, free text, and time/date interval. The administrators can also add third party sensors as a question type, which becomes an integral part of the survey on the mobile app. The administrator has the ability to create conditional branching on all of the question types, including the third party sensors which helps researchers create follow-up questions to collect all the valuable information necessary for their study.

3) User Management Module: This module allows the survey administrator to control who can access the information associated with the survey. The module helps classify the users into two different roles: participant and administrator. The administrator has the ability to add new participants, delete inactive participants, view and export data collected, and disable the survey from being accessed by the user. The participant is restricted to only take surveys through the mobile app.

4) Data Analysis and Visualization Module: This module plays an important role in data analysis and data driven decision making. The modules provide real-time information and enables researchers to set rules to get notifications triggered by the responses. Since many researchers desire to conduct more advanced analytics, the dashboard also provides the option of exporting collected data as a CSV.

IV. TigerAware Applications

TigerAware has been applied to a number of real-world studies and has shown excellent capabilities to be easily adapted and deployed for new types of data collection tasks and a wide range of studies. In this section, we first discuss feedback from an initial focus group and a pilot study and then present several on-going applications of TigerAware.

A. Privacy and Anonymity

One of the most common concerns for participants of mobile based studies (particularly clinical and behavior health studies) is privacy and anonymity [4], [14] . Thus, we have taken efforts while developing TigerAware to preserve the anonymity and privacy of participants during and after the study. When participants create a profile to be invited to a study, they can enter a coded email given to them by their research group. This will conform to IRB policies by separating participant data and identity. We also restrict the availability of surveys to people who have been assigned to them. In an effort to prevent researchers from learning about participants enrolled in different studies, we added the restriction that researchers must also know participants' study email to add them (they can't search via auto-complete, etc.). Apart from these measures, we also ensured that information is encrypted before being transmitted and that participants and researchers are authenticated.

B. Focus Group

During the development of TigerAware, we have routinely consulted with psychological and social science professionals who intend to use the application to conduct research studies. This consultation helped us gain an understanding of which components of the platform work well, and which can be improved. After development of the beta version of the platform, we gave the application to our focus group to use for two weeks. They subsequently gave feedback on five aspects of the application.

- **Usability:** Many of the researchers appreciated that the platform is intuitive, simple, and easy to use.
- **Robustness:** There was no data loss.
- **Extensibility:** The focus group recommended that TigerAware easily extend to other study types.
- **Privacy and Anonymity:** Personal anonymity and privacy of participants was a critical request.
- **Engagement:** One request of the group was to incorporate more ways of encouraging and tracking engagement of study subjects.

C. Google Assistant Based Diabetes Self Management Study

In collaboration with the Department of Health Management and Informatics at the University of Missouri, the TigerAware system was adopted for data collection and diabetes self management [5]. TigerAware was used to convert a set of questions into a Google Assistant based application, which complements an existing mobile app. A chat function was developed to collect diabetes-related information, such as the users' blood glucose readings from their Blood Glucose Monitor, daily meals and activities, and feelings.

D. Bilingualism and Aphasia Study

Though many applications exist for language learning, few allow researchers to gain an accurate understanding of language progression over time [17]. In collaboration with the University of Missouri Bilingualism and Aphasia Lab, TigerAware is used to monitor and improve the learning of new languages. For this study, an image display step type and response time metadata field is added to the framework in order to track the accuracy and speed of new word recall in Spanish and Mandarin Chinese.

E. Driving After Drinking Alcohol Study

A large body of research has examined which individuals are at risk for driving after drinking alcohol (DAD). For example, highly impulsive individuals or frequent risk takers are more likely to engage in DAD. However, almost no research has been conducted examining event-level predictors of DAD risk—what factors of the individual (e.g., current mood), drinking context (e.g., bar vs. restaurant, distance from home), or social context (drinking with one or two friends vs. party), that make a DAD event more likely. In collaboration with the University of Missouri Psychological Sciences Department and funded by an NIH grants, TigerAware is used to provide some of the first real-life data on how participants make decisions about DAD.

F. Implicit Racial Bias Study

This project studies causal inferences that racial discrimination contributes to mental health outcomes among African-Americans by characterizing the temporal relationship between racial discrimination and psychological distress. An Ecological Momentary Assessment (EMA) approach is used where African-American participants use TigerAware to report experiences of racial discrimination and momentary negative affect, anxiety, and depression symptoms (i.e. psychological distress) over a four-week period.

V. Summary

Generic and modular software tools lead to widely usable parts, which can be reused to enable rapid development. TigerAware is divided into modules that enable rapid cross platform development and extension. The TigerAware system design leads to successful multipurpose cross platform applications for different projects. Dividing TigerAware's interpretive nodes into segments effectively creates a set of parts for rapid app assembly on each of those platforms. Generic and modular development produces significant capabilities and efficiency in engineering projects, which could reduce app development time for new mobile survey based studies from months to days. TigerAware provides strong support for new wearable sensors and IoT devices, as well.

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