# Spry: Aging at Home Made Easier Using IoT Technology

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## Abstract

For the elderly population, aging comes with increased difficulty performing daily activities and an increased risk of falling. Spry aims to make it easier for members of the elderly population to live independently with a suite of first-party, comfortable and customizable devices. Therefore, our Senior Design project targets the high-risk use case of nighttime bathroom trips. In order to accomplish this, the project includes three components: hardware, IoT middleware, and a web platform. We have completed 3 of 4 planned MVP devices, functioning IoT middleware, and a web platform for end users to configure routines. We also have a vision for what Spry will look like beyond Senior Design and as a growing business catering to multiple use cases for the elderly community. Unfortunately, our work has been cut short by the COVID-19 pandemic, so our product development cannot continue and parts of the evaluation plan are hypothetical.

## 1 Motivation and Product High-Level Functionality

### 1.1 Goal

Spry's overall goal is to use IoT technology to offer a system of first-party, comfortable and customizable devices that make it easier for elderly people to live independently. Thus, our Senior Design project's goal is to build a system of Spry devices that specifically reduces the risk of nighttime falls.

### 1.2 Current Impacts on Stakeholders

The negative impact of the struggles this market faces can be seen in the risk of falls and injuries senior citizens face as they try to make their way to the bathroom at night. 1 in 4 individuals ages 65 and older fall at least once a year (Bergen et al.), and over 3 million elderly people are sent to the ER for fall-related injuries (CDC). Combined with the higher rates of conditions like visual impairment, incontinence, and benign paroxysmal positional vertigo within the elderly population, individuals are at high risks of falling and injuring themselves due to nighttime bathroom use.

Other stakeholders in an elderly individual's experience, such as concerned family members, are also negatively affected by the constant worry that comes with letting their aging loved one live alone. To reduce this worrying, family members often take additional measures to ensure their loved ones' safety, such as installing monitoring devices in the house or moving their loved ones into their own homes or assisted living facilities.

However, as senior citizens transition to living in assisted living facilities and nursing homes, the risk of falls and injuries persists as they interact with their surroundings. While nurses, a third group of stakeholders, are present to help, they must divide their time between all residents and cannot stay with each elderly resident 24/7. Reducing the risk of falling for every resident is a massive task that often leaves nurses and aids at such living facilities feeling spread too thin, making it hard for them to provide a high standard of care for every senior citizen.

Whether living alone, in assisted living, or in a nursing home, senior citizens need to be able to interact with their surroundings to use the bathroom at night without the help of others but struggle to do so successfully as they age.

### 1.3 Status Quo Solutions

Existing solutions to improving how individuals interact with their homes come in the form of IoT technology, but this technology must often be activated by voice or smartphone. For an elderly person who is not as fluent as the rest of the population with voice-activated devices or smartphones, IoT technology becomes harder to use; our survey of 40 elderly individuals and their loved ones revealed that approximately 50% hesitate to purchase assistive technology because they are concerned about the ease of setup/use or the technology's ability to understand their immigrant parents. Also, each senior citizen has different comfort levels with different IoT inputs (e.g. voice, smartphone, button, etc.), so there is no one-size-fits-all solution to reducing their barriers to IoT.

There also exist suites of products for elderly care and monitoring that are intended to detect when fall events occur and alert emergency medical responders and family members. These serve a valuable purpose by avoiding situations where fall events go undetected and the corresponding patients do not receive medical attention. However, while these fall detection products minimize the risk of catastrophic damage, they do not actually limit the risk of falls themselves. Our conversations with geriatrics experts show that even elderly people using such monitoring devices experience fear of everyday tasks that put them at risk of falling; our aforementioned survey of 40 elderly individuals and their loved ones revealed that 57.5% of people in the target age group hesitate to complete tasks like walking outside, getting up at night, climbing stairs, or moving objects (e.g. cat food) because of the associated risk of falling. In addition, the poor user interfaces described above lead to non-compliance with fall detection solutions. This is why the Spry system is intended to enable fall prevention among the elderly.

### 1.4 Our Solution

Our project includes three components: hardware, IoT middleware, and a web platform. The hardware devices can be broken down into two input devices (a pressure mat and button) and two output devices (a lighted mat to the bathroom to help with nighttime vision and a mechanized bedside handrail to help with mobility). Using the Spry system, users can choose the input devices they are most comfortable with and output devices they need. They can then log onto our web platform and register these input and output devices. Once activated, the user can set up a custom configuration on the web platform to connect their chosen input and output devices. Afterwards, they can set their devices up in their home and successfully use their input devices to activate their output devices when they get up to use the bathroom at night.

## 2 Related Work

Important aspects of our project are the use of IoT technology for geriatric care, the respect for user privacy and security through our choices to not collect user data and to secure our system at both the web platform and device layers, and the focus on fall prevention rather than fall detection. Below is a description of the related work in all three aspects of our project.

### 2.1 Academic Research

#### 2.1.1 Medical IoT Research

Cybersecurity research has begun to investigate how cyber-physical systems will be applied to home health and how individuals can remain secure in this context. Medical Cyber-Physical Systems (MCPS) are "life-critical, context-aware, networked systems of medical devices that are collectively involved in treating a patient." At present, such systems have primarily been confined to hospital and inpatient settings to focus on complex continuous care. The most prominent framework for designing MCPS is the Medical Device Coordination Framework (MDCF), which calls for Network Controller services and Supervisor services that allow for strict technological and clinical management of the system. The Network Controller allows all of the medical devices connected to the system to be connected to a device manager that tracks all of the information produced by the medical devices in a database and reads them out to a logger. The Supervisor allows for clinical services and administrative services to access the relevant information to oversee the delivery of clinical resources. Having studied the MDCF architecture, we realized that the framework introduces several security considerations that may be outside of the scope of our project. However, while the Medical Device Coordination Framework (see Appendix A) seeks to address special security issues unique to clinical connected systems (such as ensuring patient data is handled in accordance to patient confidentiality policies), there are still basic security considerations that all connected systems must address.

### 2.1.2 Security Considerations

It is a fundamental principle of network security that every node on a network can function as a potential opening into a secure system, and consequently a network is only as secure as its weakest node. As such, rigorous steps must be taken to ensure that *all* nodes are as protected as possible to ensure network security.

We realize that the functionality of Spry, which seeks to allow any user's input device to communicate with (potentially public) end effectors, creates a host of potential security vulnerabilities that should be addressed. These include the following:

- Registering spoofed devices to gain access to a user's network
- Installing an exploit on a legitimate device to gain access to a user's network, allowing remote control or monitoring of a legitimate device
- Gaining access to public networks through publically-connected end effectors
- Gaining access to the service database, compromising user account data/any stored device data (pictures, videos, usage metrics, etc.), and potentially allowing access to any connected services (i.e. medical provider networks).

To minimize the security vulnerabilities (especially in this prototyping phase), we have limited the current scope of Spry's development to focus only on devices connected to a user's personal home network, and to only allow pre-authorized devices to use the Spry service. This eliminates the security vulnerabilities inherent to connecting to devices on a publically-accessible network, and allows for tighter regulation over device nodes on the network, hopefully limiting the possibility of a spoof or device-based attack. With these limitations in place, the most significant remaining security vulnerability we foresee is if bad actors gain access to the Spry service database and compromise user data. To combat this remaining vulnerability, we plan to devote more resources to researching and implementing ways to identify and prevent unauthorized access to our service's web platform.

### 2.1.3 Fall Detection Research

While our project focuses on fall prevention, much of the work done in geriatric care thus far has focused on fall detection. Therefore, related work to our project includes the current status of fall detection technologies and the reasoning behind why there is still a need for a fall prevention product such as ours.

Much research has been conducted on automatic detection of falls by elderly individuals in their homes. The eventual goal of such research is to alert family members or medical professionals when a fall event occurs. Devices have been created that detect falls using direct patient input, accelerometers, gyroscopes, and visual sensing. Devices that require direct patient input involve requesting patient response on a physical button that they carry around to indicate if a perceived fall was not a health risk so that medical personnel are not called (Noury 2002). This is limited by potential patient incapacitation upon fall events and by the rates at which patients carry the requisite device. Solutions that use gyroscopes or accelerometers automatically detect falls using force and directional sensing coupled with computer processing of the resulting signals (Lach et al. 2009; O'Brien 2007). Such devices are often operated with the sensors built into smartphones or smartwatches, but suffer from the same setbacks of requiring that patients always carry the requisite devices (Chairi et al. 2012; Tsanakas et al. 2014). Lastly, visual sensors typically use ML approaches trained on fall videos to screen continuous video feeds for fall events (Vezzani et al. 2007; Henson 2007). This has the advantage of avoiding patient non-compliance due to device carrying, but is space-limited to wherever cameras can be set up.

However, clinical research into these devices has indicated that a combination of high false positive rates and patient non-compliance has made such devices impractical for use in the home. In addition, even if such devices worked perfectly by detecting fall events correctly 100% of the time and always monitoring patients, this would still leave much to be desired in terms of patient value. This is because detection devices do not prevent fall events from happening and this means that the damage to patient health has already occurred even if help can arrive faster. Instead, there is a clear need for research into fall prevention devices. Such devices would improve patients' interactions with the home environment and thereby decrease the rate at which the elderly have dangerous falls. This would more meaningfully address the problem in a way that is less invasive with respect to prior patient lifestyles.

### 2.2 Other Companies and Products

As mentioned in the Status Quo section, existing products and companies in the IoT smart home space revolve mostly around voice and smartphone input. Google and Amazon currently offer the largest smart home platforms, with support for hundreds of first- and third-party IoT devices. The current Middleware and IoT paradigm of a home device network consists of a smart speaker for detection of voice input, an account with the software platform provider (either Google or Amazon) and a variety of compatible IoT devices that are provisioned and controlled through the software platform. There are also many brands of smart plug, which can connect and control power to non-IoT devices, allowing for a limited degree of remote control over legacy systems.

All existing products and platforms, however, are primarily designed for non-disabled users who are comfortable with using smartphone or voice interfaces and whose main desire is convenience. These platforms are not designed with monitoring or medical needs in mind, and do not conform to the previously-mentioned Medical Device Coordination Framework. This means that it can be difficult for disabled users and their caregivers to use these existing products and platforms to do things such as track device usage, and monitor and control devices on behalf of users. As a result, there remains an open opportunity to build an ecosystem of smart home devices that serves disabled users with the security and accessibility expected when addressing medical needs and life-critical situations.

### 2.3 Open-Source Projects Used

*AWS CLI:* Unified command line interface to Amazon Web Services. We used the AWS CLI package to interact with AWS resources on the cloud from local projects, specifically when assigning certification and identification keys to allow project access into AWS.

*AWS Amplify:* Javascript library for building cloud-enabled web and mobile applications. We used AWS Amplify to interact between the web application and our AWS resources. In addition, we used an extension of AWS Amplify, "PubSub", that creates plugin sockets for the web application to publish and subscribe to our messaging middleware (the MQTT server).

## 3 Technical Approach

Our product implementation consists of three components: the web platform, the IoT hardware devices.

### 3.1 IoT Hardware Devices

We completed three hardware components, including two inputs in the form of a pressure-sensitive mat and a button and one output in the form of a lighted path. These devices can be linked into different workflows using the web platform and IoT middleware, as described below. The pressure mat input activates when the user steps out of bed and onto the mat. A set of multiplexed force-sensitive resistors are used to detect when someone steps onto any part of the mat. A Raspberry Pi (RPi) continuously reads in this data and is programmed to activate the rest of the Spry devices only once even if someone steps onto the mat with both feet. The button input activates when the user presses the button next to their bed. A RPi controlled using a Python script to recognize when the button is pressed. This is designed for users with low physical mobility or to allow them to activate the mechanized handrail before stepping out of bed. The lighted path output consists of an individually-addressable LED strip that allows users to see the path to the bathroom in low-light conditions. Several LED strips are embedded into a set of silicone mats so that they are not tripping hazards. A RPi uses a Python script to listen for messages from input devices and controls the colors/brightness of each individual LED. A fourth device, in the form of a mechanized handrail output, was near completion before the hardware components were rendered inaccessible due to the COVID-19 outbreak. It lies stowed away next to the user's bed until activated by the input devices, at which point it swivels into position to allow users to get out of bed while stabilizing themselves using the handrail. The team completed functional prototypes of this device, but not the finished product.

### 3.2 IoT Middleware

The IoT middleware allows our devices to communicate with each other and with the web platform through the Message Queuing Telemetry Transport (MQTT) protocol. MQTT is structured like a typical client-server model, requires minimal network bandwidth and runs in real-time, making it the preferred form of message transmission for IoT systems. Messages are passed through "topics" that applications are subscribed and can publish to. The AWS IoT Platform serves as our MQTT broker (i.e., server) while the web platform as well as each hardware device is registered as an IoT "thing" (i.e., clients). Our infrastructure is built and secured at two levels as follows: At the first level, after web authentication, we dynamically generate permission policies to provide each unique user access onto the platform. Then, at the second level, the user communicates only with devices that are subscribed to topics containing parts of the user's credentials. Topic names are therefore structured to embed user identification information, limiting a user's ability to communicate only through their own designated channels. In addition, we control the directionality of communication by providing various subscription and publication functionalities to the devices and the web platform. The web platform can communicate and receive feedback (to verify connection) from any connected device. Input devices can send signals (e.g., "turn off," "lift up") to output devices and also receive messages from the web platform regarding where to send these signals. Output devices receive messages from both the web platform and input devices but are only allowed to publish to the web platform.

### 3.3 Web Platform

The web platform is built using a React frontend, Node backend and offers a simple interface for elderly users or their loved ones to manage their Spry accounts, devices, and routines. Functioning features of the platform include user registration/login, for which authentication is done using Amazon Cognito and all new accounts are also stored in a User datatable for later updates to user configurations. A second functioning feature is device registration, where users can register input/output devices using preset device info that is verified against our InputDevice and OutputDevice datatables. Device registration also triggers communication between the web platform and the registered device using the IoT middleware, enabling the device to store the user's Cognito information for future verification of messages sent from other devices or the web platform. Lastly, the web platform enables the creation/updates of connection groups, so that users can choose which of their activated input and output devices they would like to use to set up their customized routine (e.g. nighttime bathroom use). Creating a connection group triggers communication between the web platform and relevant devices, storing the list of devices each device is connected to on the hardware itself. The web platform functions using a combination of Amazon API Gateway, Lambda functions, and DynamoDB for updating device configurations.

## 4 Evaluation

### 4.1 Quantitative Evaluation

#### 4.1.1 Response Time

The average motorist has a reaction time of 0.8 seconds (less than one second). For usability purposes, we benchmarked the speed of our IoT system to this average response time as a way to evaluate if we have a product capable of delivering real-time assistance to the elderly. Understanding that traditional REST API calls over HTTP are slower than API calls over MQTT, we chose to implement our system's communication network using MQTT in effort to meet this benchmark. We have completed the communication infrastructure between our input and output devices and after testing (e.g. pressing a force sensor to activate lights), our output devices responded with perceivably instantaneous speeds to our eyes. Research has shown that the brain can process images we see for even just 100ms, and we believe this time is a sufficient indicator of what is considered "instantaneous speed" to the naked eye. Given 100ms is also well below one second, we believe our product is well-built to service users in real-time.

#### 4.1.2 Usability

The usability of the devices and platform were evaluated using a user survey sent out to adults with elderly parents as well as to elderly adults during the spring semester; the survey consisted of 40 responses. To the elderly adults, we asked if they live independently, what daily activities they struggle with, if they would be open to using devices to assist them, and if they would be comfortable specifically with using the Spry product. 100% of the elderly adults we surveyed indicated that they would be comfortable using the Spry products and do feel it could help them in their daily activities. Additionally, all respondents indicated that they commonly use the restroom in the middle of the night. From the survey sent to adults with elderly parents, we asked if they would be comfortable purchasing assistive devices for their parents, what safety concerns they worry the most about in regards to their elderly parents, whether they have taken actions already to ensure the safety of their parents, and if they would be comfortable with their parents living alone with the Spry product. From the survey, 82.5% of responses indicated that they worry about their parents falling or getting injured and have taken precautions. The majority indicated that they are not satisfied with the options available. Additionally, 95% of adults indicated that they would be willing to purchase and set up the Spry product for their parents and would be comfortable having their parents live alone if they had this device. They do feel it is a simple product to use and that it would be easy to have their parents adjust to living with these devices.

#### 4.1.3 Costs

Throughout this project, we have incurred costs for each input and output device sold. The detailed breakdown of the costs for each device can be found in the Business Analysis section. The costs of the Spry system are low enough at the research scale to test devices and sell them to early adopters and the costs at the production scale are low enough to garner large margins upwards of 80%. Importantly, the costs at both scales are lower than the willingness to pay of 92.5% of seniors over the age of 65 and children of seniors in the former group, the two entry points into the target market, as determined in the aforementioned survey of 40 individuals conducted in the spring semester. This would allow Spry to price its set of devices to include profit margin and to include the pure-profit $125 fee for access to the software platform. Thus, the Spry system has a sufficiently low cost to be profitable and to be accessible to the target market at the research and early production scales.

### 4.2 Evaluation Plan

#### 4.2.1 Device Effectiveness

Each of our 3 completed devices, both input and output, must be evaluated individually based on their primary role in the Spry IoT system. As such, we have come up with the following preliminary quantitative evaluation plans for each of the four devices we have constructed.

*Device Brightness (for Lighted Mat)*

We envision evaluating the effectiveness of our lighted mat output device by measuring the brightness of the activated state (in lumens) and comparing to the average lumens used in standard safety lighting, such as exit signs and lighted exit pathways in buildings. Measurement of the lighted mat's output brightness would be conducted in a standardized room with a light meter. Average lumens used in standard safety lightings would be determined by referencing building safety codes available online.

*Weight Detection (for Pressure Pad)*
We envision evaluating the effectiveness of our pressure pad input device by measuring the minimal detectable weight and comparing it to the anticipated range of body weights in the targeted user population. To measure the minimal detectable weights, we will use a standard weight and place it on the pressure pad to see if it was detected. We would then increase the weight in standard increments until the force was detected. The average body weight range would be determined from demographic studies available.

*Necessary Activation Force (for Button)*
We envision evaluating the effectiveness of our Button input device by measuring the minimum force needed to depress the button and comparing it to the average strength of a user in the targeted user population. The minimum force needed to activate the button would be determined by placing objects of decreasing weight on the button until it no longer depresses. The average strength of a target user would be determined from demographic studies available online.

### 4.2.2 Usability

Aside from evaluating the technical functionality of our system, we planned to evaluate the system's usability among elderly people through user interviews and focus groups at the Ralston Mercy-Douglas House (originally scheduled for March 25, 2020). These interviews and focus groups were intended to evaluate the time required for an elderly person to learn how to use the product, an elderly person's ability to access the devices in their rooms and in low-light settings, and the percentage of elderly people who find a comfortable input device to use with our system.

*Learning Time*
We envision our target user, an elderly person, to learn how to use our product in under 15 minutes, inclusive of us explaining our system. Our benchmark of 15 minutes is based on the average attention span of 20 minutes of adults, with a penalty for the reduction in attention span that people face as they age. Our procedure for testing our system against this metric would be to do individual user interviews with at least 20 elderly residents at Ralston House and time the duration from our introduction of the system to them being able to use an input device to activate an output device. Our final measure would be an average of the time taken by each elderly resident interviewed.

*Input Device Detection/Use in Dim Environments*
With respect to our input devices, we want to know if they can be intuitively placed in the average room for the elderly citizen to easily access, and if not, how we can improve their structures. We envision our input devices may be used in low-light conditions, such as when the user gets up in the middle of the night. As such, we plan on evaluating how easy it is to find and use our two input devices, the pressure pad and the button, when the user cannot see clearly due to lack of illumination. For example, we intend to test if a user can easily wake up and find a button situated somewhere close to their bed in the darkness of the night. Such analysis will likely be performed by placing users in a simulated condition and tasking them with finding and using the input devices. This would likely require utilization of the Home Care Suite access given to us by Penn Nursing. Rates of user success as well as qualitative user feedback would likely be our main metrics for evaluation.

*Comfort*
We envision our current system being able to provide comfortable input devices to at least 30% of the elderly population. We set a lower benchmark here with the knowledge that there are far more input device options possible than the two we have built out. Our procedure for testing our system against this metric would be to ask at least 20 residents at Ralston House, either during individual interviews or during a focus group, to choose between the pressure pad, the button, or neither for which device they would use to activate the output devices.

## 5 Societal Impact

One of the main objectives of the Spry system is to generate a net-positive societal and ethical impact on its users' quality of life.

From a societal perspective, Spry aims to enable the elderly community to live more independently, while taking steps to mitigate the possibility of creating a false sense of security for the elderly and their families. Such mitigation strategies currently center on developing user education materials that teach proper use of the Spry system, so that users can maximize their benefits and be cognizant of the system's limitations. Additionally, we identified the adult children of elderly users as a potential access point to the end user market, implying that the adult children would be involved in the set up of the Spry system if the end user was not capable of setting up the system themselves.

From an ethical perspective, Spry aims to provide an inclusive solution that equitably serves people with different capabilities, while working to minimize the vulnerability of users to privacy breaches and bad actors. To address such vulnerabilities, the Spry team is strongly committed to not collecting user-identifiable data, and investing in multiple layers of authentication and digital security, such as AWS Cognito.

One relevant question raised by peers was how the Spry system would minimize the harm done by malfunctioning assistance devices. To address this, Spry-enabled devices can have built-in indicator lights to alert the user to hardware failure, and minimum activation thresholds to prevent accidental activation of devices. This is also where Spry's investment in user education materials can help ensure users can identify malfunctions and are aware that like most home equipment devices, Spry hardware also may be subject to breakage or malfunction unrelated to operator error.

## 6 Discussion and Lessons Learned

While unfortunately we were unable to iterate on our product through user testing due to the COVID-19 outbreak, we do have several takeaways from our design process and the journey toward building an integrated platform:

### 6.1 Lessons Learned

#### 6.1.1 Customer Awareness

Over the course of the project, we had many opportunities to interact with senior citizens as well as present concerns about their personal, physical limitations on their behalf to a public audience. This experience taught us that to develop a deeper understanding of what our customers cared about, we needed to become aware of their habits and feelings. We highlight a particular case: before we reached out to survey seniors living in assisted facilities, we met with an advisor, Dr. Demiris, to discuss the questions we had planned for the user study. He instructed us that the wording we use can influence the results of the study, particularly when the target group are elderly individuals. We had planned to begin the study by asking whether each participant suffers from a set of different common problems that can beset the elderly. However, a more productive framing for questions like this is to comment that many elderly people have particular issues and then ask if they are one of the people in this group. This approach can help because it reduces the tendency for people to minimize their portrayal of the struggles that they face by first making them feel like those struggles are shared by many other people. This could help us to reduce bias in our user studies.

#### 6.1.2 Security & Functionality Go Hand-in-Hand

Our initial instinct when building out prototypes of how the hardware devices, IoT middleware, and web platform would work together was to ensure functionality first and add security features later. However, through our process of establishing the IoT middleware to funnel communication between devices and the web, we discovered that implementation of security systems can and should occur alongside building functionality. At the onset of our project, we were concerned about how we would be able to ensure that only a particular user can control their specific devices. We thought that this security feature would only be considered *after* we had built out the initial connections between our devices. However, we learned that we could control the structure of these communication channels (i.e. MQTT topics) by setting access restrictions to users from the web platform as well as structuring the topics tree such that users needed additional permissions to have subsequent communication abilities with each additional device. Therefore, how we chose to implement the communication infrastructure itself affected the security of our system.

### 6.2 Future Work

Future development of Spry will focus on expanding the suite of input and output devices as well as the platform into a full-fledged system that can be utilized by external users for use cases beyond a nighttime bathroom visit. This could be for other high-risk cases in the home such as those in the laundry room and kitchen. Collectively, future work will expand the functionality of Spry and allow it to better improve the independence of senior citizens throughout the home.

## 7 Business Analysis

### 7.1 Overview of Problem and Need

Research into geriatrics technology has given elderly people access to products that attempt to detect falls in the home. However, most such products do not take the technological capabilities or user interface design preferences of the elderly into account. This has led to low usage rates of detection technology due to patient non-compliance, even in homes where it is installed. As a result, such systems fail to alleviate the root cause of the danger to elderly people living independently in their homes. Therefore, Spry is focused on preventing fall events, rather than just detecting them. In order to do this, Spry-enabled devices focus on the home workflows that put people in the target market most at risk. Nighttime bathroom visits are the most common source of fall events, so the first-party Spry devices discussed here integrate into the routines of independent seniors to mitigate this risk. The platform is designed to allow other organizations to build their own third-party Spry-enabled devices and make them available on the platform to address other high-risk use cases like moving around the kitchen and laundry room. This allows the platform to expand to address more customer needs over time.

### 7.2 Value Proposition

The Spry device system helps senior citizens live independently and free from fear of falling through a customizable and comfortable home IoT experience.

### 7.3 Key Stakeholders

*Elderly people:* The market for assisted living devices is created by the risks that these end users face as they age. Over 3 million older people a year are sent to the ER for fall-related injuries, and most elderly falls happen at night (when seniors are more visually impaired or are moving recklessly as they rush to reach the bathroom).

*Concerned family members:* Letting an aging loved one live alone results in constant worry for family members. To reduce this, family members often take extra measures to ensure their loved ones' safety, such as installing monitoring devices in the house or moving their loved ones into their own homes or assisted living facilities.

*Clinicians/Nurses:* Staff are heavily involved with elderly people who do transition to assisted living facilities and nursing homes. These employees are present to help elderly residents, but they must divide their time between all residents and cannot stay with each individual 24/7. Reducing the risk of falling for every resident is a massive task that often leaves nurses and aides at such living facilities feeling spread too thin.

### 7.4 Market Opportunity & Customer Segments

Elderly individuals are the clear end users of Spry, but the above description of stakeholders involved in their home living experience reveals a few different target customer segments:

*Tech-savvy grandparent:* Middle/upper class individual, age 65 or older, who lives independently and welcomes technology into the home. Is looking for ways to improve surroundings so they can continue to live alone, and sees the Spry system as an interesting project.

*Concerned son/daughter:* Middle/upper class individual who has older parents who have fallen in the past or are beginning to struggle with incontinence. Either wants to help their parents continue to live independently, or wants to move their parents but needs alternatives because their parents refuse.

*Assisted living facility/nursing home director:* Has a large number of elderly residents in their nursing home or assisted living facility, and has a staff that is unable to spend enough time with each resident to help with daily tasks like nighttime bathroom use. Is looking for simple, secure, and large-scale ways to reduce their staff's workload and improve their residents' independence. This customer segment is not our primary target during Spry's initial growth, but provides a potential customer base to expand to at a later stage.

### 7.5 Size and Growth of Market Segments

Because both target customer segments mentioned above will be purchasing Spry products for the same end users, elderly people, we group them together to estimate size of the market. As of 2015, there were 47.8M people over the age of 65 in the US. By 2024, this population will grow to about 70M. Of the 70M, about 5% will be living in nursing homes and care facilities which have different purchasing and churn patterns, resulting in the remaining 66.5M seniors still living in their own homes. A typical split of the elderly demographic has 65% of seniors living alone (~43M potential customers) and 35% with a spouse (half of 35% of 95M ~12M potential customers). We arrive at a Total Addressable Market (TAM) of ~55M customers. The current market penetration of wearables in the ages 65+ population is 17%. With the known stigma against wearables among the elderly, we see 15% market penetration as a reasonable estimate for Spry, giving us a total opportunity of ~8M customers (see Appendix B).

### 7.6 Competition

Our main competitors are other smart home device platforms and non-IoT assisted living devices.

*Voice-activated device platforms:* Amazon Alexa and Google Home are leaders in this market, with a wide range of compatible third-party devices and the brand recognition to incentivize further device integration. Their disadvantages in the elderly customer segment are usability (older people have trouble understanding the behavior change) and trust (older people are especially sensitive to the "always listening" concept).

*Button-activated device platforms:* Flic offers a smaller range of compatible third-party output devices, but has a button-based activation system that reduces the elderly's trust concerns. Their disadvantage with this customer segment is usability (buttons may work for some older people but are uncomfortable for others).

*Non-IoT assisted living devices:* Assisted Living Technologies sells a wide range of sensing, monitoring, and home safety devices to be installed in an elderly person's home, providing targeted solutions for the various risks associated with aging. Their disadvantage is the learning curve associated with installing each third-party device, and the lack of customization available to the user.

### 7.7 Cost

*Fixed Costs:* Production of the Spry system requires fixed costs for software development and business operations and variable costs for device materials and assembly. Software development costs are primarily composed of the salaries of software engineers and the semi-fixed costs of web hosting. Since Spry is targeting elderly individuals and their families, customer service representatives will be more valuable to them than an FAQ page online, so this will also be a semi-fixed cost. The software package that operates the Spry system will have a user-facing price associated with it to cover these fixed costs.

*Variable Costs:* Spry will incur variable costs for each input and output device sold. For instance, the costs for the pressure pad input device at R&D

scale include $35.00 for a Raspberry Pi 4, $7.95 for a power supply, $3.99 for a force-sensitive resistor, and $6.88 for a floor mat for a total of $53.82. At a larger production scale of 1000 devices, the Raspberry Pi could be replaced with a PCB that would cost $0.04 and other integrated circuit components such as a Wi-Fi module costing $1.00. This would bring the production-scale cost to $13.98 per unit. This scale could allow for bulk purchasing of the other components that could further decrease the cost. Using a similar methodology, the cost of the input button would be $43.95 at R&D scale and $9.99 at early production scale. Likewise, the cost of the output LED pathway would be $77.83 at R&D scale and $14.99 at early production scale. The unit costs of the mechanized hand rail are currently to be determined.

### 7.8 Revenue Model

We intend to generate revenue through two, top-line segments: "Software" and "Devices." The Software stream is a traditional product package that consists of the Spry integrated IoT system. We chose to sell through stand-alone packages as opposed to a Software-as-a-Service model due to the elderly population's aversion to paying recurring, subscription fees. Purchasing this software gives users the *ability* to install Spry devices into their homes. The Devices segment accounts for revenue from the sale of individual Spry hardware (e.g., buttons, lights). Based on results we gathered from surveying a group of seniors and their family members, we estimate the typical spend of a potential user is likely to be around $250: $125 for the software and between $50 - $75 for an average of two additional devices (one input and one output) purchased. This average spend may increase once family members see the devices in action as they indicated a much higher willingness to pay based on the value it could provide to their parents.

Given these unit economics, we estimate our market value using the ~8M customers previously described. With each customer spending an average of $250, we are going after a market value of ~$2B. Industry experts anticipate the senior "home care" market to reach $224B by 2024 (inclusive of services), implying that Spry would be able to capture ~1% of this total market, which we see as a reasonable and feasible approximation. For detailed estimates on the revenue model and cost structure, see Appendices C and D.

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## 9 References

ASC Care. Assisted Living Statistics and Facts (2019).

Bergen G, Stevens MR, Burns ER. Falls and Fall Injuries Among Adults Aged ≥ 65 Years — United States, 2014. MMWR Morb Mortal Wkly Rep 2016;65:993–998. DOI: http://dx.doi.org/10.15585/mmwr.mm6537a2

Bourke, A., O'Brien, J., & Lyons, G. (2007). Evaluation of a threshold-based tri-axial accelerometer fall detection algorithm. Gait & Posture, 26(2), 194–199. doi: 10.1016/j.gaitpost.2006.09.012

Centers for Disease Control and Prevention, National Center for Injury Prevention and Control. Web–based Injury Statistics Query and Reporting System (WISQARS) [online]. Accessed November 1, 2019.

Cucchiara, R., Prati, A., & Vezzani, R. (2007). A multi-camera vision system for fall detection and alarm generation. Expert Systems, 24(5), 334–345. doi: 10.1111/j.1468-0394.2007.00438.x

Demiris, G., Rantz, M. J., Aud, M. A., Marek, K. D., Tyrer, H. W., Skubic, M., & Hussam, A. A. (2004). Older adults' attitudes towards and perceptions of 'smart home' technologies: a pilot study. Medical informatics and the Internet in medicine, 29(2), 87-94.

Demiris, G., & Hensel, B. K. (2008). Technologies for an aging society: a systematic review of "smart home" applications. Yearbook of medical informatics, 17(01), 33-40.

Demiris, G., Hensel, B. K., Skubic, M., & Rantz, M. (2008). Senior residents' perceived need of and preferences for "smart home" sensor technologies. International journal of technology assessment in health care, 24(1), 120-124.

Doñate-Martínez, A., Ródenas, F., & Garcés, J. (2016). Impact of a primary-based telemonitoring programme in HRQOL, satisfaction and usefulness in a sample of older adults with chronic diseases in Valencia (Spain). Archives of gerontology and geriatrics, 62, 169-175.

Institute on Aging. Information on Senior Citizens Living in America.

Institute of Medicine (US) Food Forum. Providing Healthy and Safe Foods As We Age: Workshop Summary.

Jumani K, Powell J. Benign Paroxysmal Positional Vertigo: Management and Its Impact on Falls. Annals of Otology, Rhinology, and Laryngology, 2017 Aug, DOI: 10.1177/0003489417718847

Lee, I., & Sokolsky, O. (2010, June). Medical cyber physical systems. In Design automation conference (pp. 743-748). IEEE.

Li, Q., Stankovic, J. A., Hanson, M. A., Barth, A. T., Lach, J., & Zhou, G. (2009). Accurate, Fast Fall Detection Using Gyroscopes and Accelerometer-Derived Posture Information. 2009 Sixth International Workshop on Wearable and Implantable Body Sensor Networks. doi: 10.1109/bsn.2009.46

Maglogiannis, I., Ioannou, C., Spyroglou, G., & Tsanakas, P. (2014). Fall Detection Using Commodity Smart Watch and Smart Phone. Progress in Pattern Recognition, Image Analysis, Computer Vision, and Applications Lecture Notes in Computer Science, 70–78. doi: 10.1007/978-3-662-44654-6_7

Mellone, S., Tacconi, C., Schwickert, L., Klenk, J., Becker, C., & Chiari, L. (2012). Smartphone-based solutions for fall detection and prevention: the FARSEEING approach. Zeitschrift Für Gerontologie Und Geriatrie, 45(8), 722–727. doi: 10.1007/s00391-012-0404-5

Mount J, Kresge L, Klaus G, Mann L, Palomba C. Movement patterns used by the elderly when getting out of bed. Department of Physical Therapy Faculty Papers, 2006 July, https://jdc.jefferson.edu/ptfp/2

Noury, N. (n.d.). A smart sensor for the remote follow up of activity and fall detection of the elderly. 2nd Annual International IEEE-EMBS Special Topic Conference on Microtechnologies in Medicine and Biology. Proceedings (Cat. No.02EX578). doi: 10.1109/mmb.2002.1002337

Options for Senior America. Facts, Statistics, and Numbers About Home Health Care: Options for Senior America.

Rajkumar, R., de Niz, D., & Klein, M. (2017). Medical Cyber-Physical Systems. In R. Rajkumar, D. de Niz, & M. Klein, Cyber-Physical Systems (pp. 1-6). Pearson.

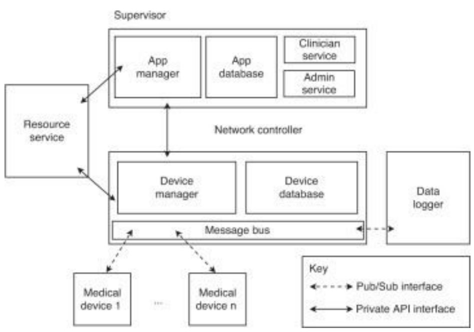
Soliman Y, Meyer R, Baum N. Falls in the Elderly Secondary to Urinary Symptoms. Rev Urol. 2016;18(1):28-32. PMID 27162509; PMCID: PMC4859925.

Srinivasan, S., Glover, J., & Bouknight, J. G. (Eds.). (2017). Geriatric Telepsychiatry: A Clinician's Guide. Springer.

Williams, A., Ganesan, D., & Hanson, A. (2007). Aging in place. Proceedings of the 15th International Conference on Multimedia - MULTIMEDIA 07. doi: 10.1145/1291233.129143

## 10 Appendices

### *Appendix A. Medical Device Coordination Framework*




(Rajkumar, de Niz, & Klein, 2017)

### *Appendix B. Total Addressable Market*

| (MM customers) | 2020E | 2021E | 2022E | 2023E | 2024E |
|---|---|---|---|---|---|
| Senior pop. | 60.1 | 62.6 | 65.1 | 67.5 | 70.0 |
| *% in nursing care* | *5%* | *5%* | *5%* | *5%* | *5%* |
| Seniors living at home | 57.1 | 59.5 | 61.8 | 64.2 | 66.5 |
| *No spouse* | *37.1* | *38.7* | *40.2* | *41.7* | *43.2* |
| Potential customers | 37.1 | 38.7 | 40.2 | 41.7 | 43.2 |
| *With spouse* | *20.0* | *20.8* | *21.6* | *22.5* | *23.3* |
| Potential customers | 10.0 | 10.4 | 10.8 | 11.2 | 11.6 |
| Total addressable market | 47.1 | 49.1 | 51.0 | 52.9 | 54.9 |
| *% Spry penetration* | *3%* | *6%* | *9%* | *12%* | *15%* |
| Total potential Spry customers | 1.4 | 2.9 | 4.6 | 6.4 | 8.2 |

### *Appendix C. Revenue Model*

| ($MM) | 2020E | 2021E | 2022E | 2023E | 2024E |
|---|---|---|---|---|---|
| Software | | | | | |
| Customers | 1.4 | 2.9 | 4.6 | 6.4 | 8.2 |
| Price | 125.0 | 125.0 | 125.0 | 125.0 | 125.0 |
| Total software revenue | 176.7 | 368.0 | 573.7 | 793.9 | 1028.7 |
| | | | | | |
| Devices | | | | | |
| Customers | 1.4 | 2.9 | 4.6 | 6.4 | 8.2 |
| Avg. qty per customer | 2.0 | 2.5 | 3.0 | 3.5 | 4.0 |
| Avg. price | 50.0 | 50.0 | 50.0 | 50.0 | 50.0 |
| Total devices revenue | 141.4 | 368.0 | 688.4 | 1111.5 | 1645.9 |
| | | | | | |
| Total revenue | 318.1 | 735.9 | 1262.2 | 1905.5 | 2674.5 |
| *% yoy* | - | *131.3%* | *71.5%* | *51.0%* | *40.4%* |

### *Appendix D. EBITDA*

| ($MM) | 2020E | 2021E | 2022E | 2023E | 2024E |
|---|---|---|---|---|---|
| Revenue | 318.1 | 735.9 | 1262.2 | 1905.5 | 2674.5 |
| Cost of sales | | | | | |
| Avg. total devices | 2.8 | 7.4 | 13.8 | 22.2 | 32.9 |
| Avg. cost / unit | 15.0 | 15.0 | 15.0 | 15.0 | 15.0 |
| Total COGS | 42.4 | 110.4 | 206.5 | 333.5 | 493.8 |
| Gross profit | 275.7 | 625.6 | 1055.6 | 1572.0 | 2180.8 |
| *% margin* | *86.7%* | *85.0%* | *83.6%* | *82.5%* | *81.5%* |
| SG&A | 238.6 | 478.4 | 694.2 | 857.5 | 936.1 |
| *% of sales* | *75.0%* | *65.0%* | *55.0%* | *45.0%* | *35.0%* |
| R&D | 63.6 | 147.2 | 252.4 | 381.1 | 534.9 |
| *% of sales* | *20.0%* | *20.0%* | *20.0%* | *20.0%* | *20.0%* |
| EBITDA | (26.5) | 0.0 | 109.0 | 333.5 | 709.8 |
| *% margin* | - | *0.0%* | *8.6%* | *17.5%* | *26.5%* |