Chapter 1: Introduction

Nate Bachmeier

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Northcentral University

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A demographic change will create significant pressure on the global health care system because people live longer, have fewer children, and medical costs continue to increase (Piggott, 2016; Stone, 2017). When patients cannot afford the required care, the quality decreases, or social programs must fund the difference. Demographic specialists predict that by 2050 nearly “80% of the global elderly population will be from low- to middle-income countries (Mushsin et al., 2020, p. 1).” Economic constraints within those countries will limit the effectiveness of their welfare programs and the availability of adequate services. Additionally, over one billion globally have a limiting disability that requires additional support (Morris, 2008). Medical facilities need mechanisms to defuse the situation by reducing costs and deferring the transition to assisted living centers.

Inversely, the explosive growth across IoT, cloud, big data, and mobile (ICBM) continuously decreases costs and enables new opportunities. These technologies have the potential to revolutionize the health care and wellbeing industries. Academic and commercial vendors are continually delivering innovations across these domains. However, mainstream offerings primarily focus on measuring simple body metrics (Koreshoff, Robertson, Leong, 2013). While these products provide incremental value, they do not move the needle. Nearly eight years later, the industry myopically drives toward wearable IoT devices (Tun et al., 2021). Researchers concentrating on these areas make sense due to the low barrier to entry. Though, that same ease is commoditizing the product selection and stifling creativity.

Technology within special needs and elderly care settings has unique challenges and requirements (Ferati et al., 2016). These persons need unobtrusive systems that continuously monitor and respond to their behaviors. Specific vendors utilize voice-enabled Personal Digital Assistants (PDA) (e.g., Amazon Alexa) to effectively set reminders and record activities (Tan et al., 2020). However, it becomes challenging to globalize these voice-specific technologies to assist non-native speakers and individuals with vocal disorders.

Assisted living facilities use trained nurses to mitigate these issues. Having a human inspect the patient visually is an effective but expensive tool. The median compensation rate for registered nurses is $75,330 annually ($36.22 per hour) (US Bureau of Labor Statistics, 2020). Due to the high cost, few patients have private nurses and receive fractional supervision. In contrast, video-centric monitoring and Human Activity Recognition (HAR) apply to a diverse population. When a person falls or drinks a glass of water, their skeleton moves in predictable ways. This consistency enables artificial intelligence & machine learning (AI/ML) to respond through cyber-physical systems (CPS). Businesses could deliver these capabilities economically and consistently across global markets, ultimately improving the quality of care at lower costs.

However, ethical concerns and privacy issues prevent researchers from collecting data at scale (Lei et al., 2021). Imagine the complexity that small-to-medium businesses face between vetting volunteers and ensuring diversity across participants. There are also budgetary considerations to deploying IP cameras and other CPS in numerous households (Shirazi & Shekhani, 2021). These challenges prevent quality research from occurring and improve patients’ quality of care. Instead, processes must exist to simulate these interactions and iterate toward more sophisticated systems.

## Statement of the Problem

The problem to be addressed in this study is the inability of elderly and special needs care organizations to implement autonomous assistants and divest from manual labor (Kim & Kim, 2021; Blackhurn, 2021). Multiple industry-wide trends create the need for this technology. First, the number of practicing nurses has declined for several years (Kim & Kim, 2021). This labor shortage increases hiring and employee retention costs that the patients and welfare programs must cover. The funding gap is a global problem that does not impact all communities equally. For instance, in South Africa, rural special needs communities have 57% fewer nursing visits than their urban neighbors (Besada, 2020). Newly industrialized economies like Taiwan, South Korea, Thailand, and Malaysia are experiencing challenges maintaining their long-term care programs due to growing costs (Phua, 2021). Domestic programs like Veterans Health Administration (VHA) and Medicare are not immune to these economic limits (Lei et al., 2021). Businesses and governments must control these costs and replace human labor with less expensive automation.

Beyond human and process issues are technical complexities in configuring prototype autonomous assistants. It requires multiple domain specializations like computer networking, embedded technologies, AI/ML, and distributed computing (Tun, Madanian, & Mirza, 2021). Each cross-cutting concern adds complexity and reduces the probability that small teams can successfully provision their test environment. Furthermore, those difficulties limit other researchers from reproducing the results. These factors slow innovation and restrict the value researchers can contribute to the body of knowledge.

## Purpose of the Study

This study examines the feasibility of predicting virtual patient behaviors using motion-capture animations. For instance, hemodialysis patients have a high risk of falling and becoming injured (Shirai et al., 2021). Similarly, early dementia patients need monitoring capabilities to assist with discovering objects and providing task management (Lei et al., 2021). It would be time-consuming and potentially dangerous to use humans, which invites the need for artificial agents. The research uses a virtual environment that divorces privacy and safety concerns from investigating autonomous assistants in elderly and special needs care. It aims to deliver this capability by utilizing artificial agents within a realistic physics simulation process like PhysX or Gazebo (Bipin, 2018; Unreal, 2021). These engines support replaying specific motion-capture animations (MoCAP) under varying character properties such as weight, flexibility, and dexterity. Next, positioning virtual cameras, instruments, and devices within the virtual world enables the study to collect experimentation data. Lastly, the automation can modify the environment using programmable interfaces such as raising the alarm or applying other mitigations.

The study focuses on a finite action space like hemodialysis because of its medical importance and access to training data (Shirai et al., 2021). This situation negatively impacts their quality of life by either remaining in bed or requiring more medical resources. The study explores this use case by virtualizing the patients and monitoring them with an AI/ML computer vision (CV) process to collect metadata and predict a fall in advance. Human trials prioritize safety, creating challenges to study metadata properties like floor slickness and character overexertion (Aihara et al., 2021). In contrast, humanoids are well-suited for these experiments. Furthermore, the lack of privacy concerns simplifies the video collection in bathrooms and showers.

Robot operating systems (ROS) and similar toolchains support generating dozens of floor plans and filling them with furniture (Bipin, 2018; AWS RoboMaker, 2021). These services streamline experimentation, allowing the research to focus on the patient requirements versus simulation infrastructure. The study will use these capabilities to verify the AI/ML CV process across a reproducible gradient of character properties (e.g., weight from 80 to 500 lbs and age between 30 to 120 years).

## Introduction to Theoretical Framework

Design of experiments research creates purposeful artifacts and applies them to study a phenomenon (Hevner et al., 2004). Academic and business communities employ this method as a standard approach to Information Technology and Communication (IT&C) problems (Peffers et al., 2007; Bryar & Carr, 2021). It has well-defined guidelines (see Table 1) to implement a three-phased procedure. First, the researcher(s) must identify a domain-specific challenge. Next, that researcher creates artifacts that study this phenomenon. Third, those artifacts assess the topic and communicate answers to the research questions.

Table 1:   
*Design-science Guidelines (Hevner et al. 2004)*

|  |  |
| --- | --- |
| Guideline | Description |
| Design as an Artifact | Design-science research must produce a viable artifact as a construct, a model, a method, or an instantiation. |
| Problem Relevance | Design-science research aims to develop technology-based solutions to important and relevant business problems. |
| Design Evaluation | A design artifact's utility, quality, and efficacy must rigorously demonstrate well-executed evaluation methods. |
| Research Contributions | Effective design-science research must provide transparent and verifiable contributions to design artifacts, foundations, and/or design methodologies. |
| Research Rigor | Design-science research relies on rigorous methods to construct and evaluate the design artifact. |
| Design as a Search Process | The search for a compelling artifact requires utilizing available means to reach desired ends while satisfying laws in the problem environment. |
| Communication of Research | Design-science research must be presented effectively both to technology-oriented and management-oriented audiences. |

This study uses these guidelines and conceptual steps to identify a research-worthy topic and an actionable aspect. Next, it defines an abstract approach and implements a concrete proof-of-concept, the simulation process, to assess patient monitoring (via CV) and remediation (via CPS) technologies. Third, the artifacts expand the body of knowledge through the research questions. See Chapter 3: Research Method for more information.

## Research Questions

This constructive research design study proposes a research method for modeling elderly and special needs behaviors. Using an AI/ML CV monitoring process to predict HD patients’ likelihood of falling within a physics simulation process seeks to demonstrate this approach. That proposition raises questions regarding the potential solution’s ability to detect and respond to patient behaviors.

### RQ1

To what extent can the CV-based system extract the subject’s *intent* from dynamic and noisy video streams? The virtual patient can freely roam within their residence and modify the environment, such as moving furniture and turning off lights. Does this impact the reliability of the statically positioned camera?

### RQ2

To what extent can the AI/ML monitoring process predict that the patient will fall? The humanoid and physics engine will honor rules, such as steps until the fall is proportional to the character’s weight and height. Can the process learn these rules and demonstrate the generalizability to more specific medical situations?

## Significance of the Study

Human activity recognition (HAR) can improve elderly and special needs care by efficiently scaling out the visual coverage of medical facilities. Today, it is challenging to study HAR solutions within private residences. These issues stem from the system needing to record and share potentially privacy-sensitive situations, such as bathing or intimacy. Further complicating matters, the researchers must overcome the logistical challenges of finding representative samples, proving result reproducibility, and the economic overhead of multiple monitoring stations. Instead, this study proposes a research process using a physics simulator, animated actors, and virtual homes. The novel approach enables researchers to assess their CV algorithms across a repeatable configuration corpus. For instance, elderly patients falling is one of the most significant and avoidable reasons they need medical attention. This approach simulates this scenario, with each limb having distinct tensile strength, flexibility, and weight. When researchers can generate representative test cases economically, it unlocks the potential for faster product iterations and quickly expands the body of knowledge.

Cyber-physical systems (CPS) serve as a bridge between digital algorithms and the real world. These technologies need patterns and methodologies that react to intents discovered through HAR. Today, the fractured ecosystem spans multiple vendors, and it is cumbersome to assess holistic solutions. This research project aims to reduce this complexity with specific virtual health and safety devices compatible with the simulator. Future researchers can leverage these tools and services to introduce noise (e.g., camera distortion) into the virtual world. Further lowering the barrier to entry for study HAR within personal residences opens the door to future innovations not yet considered!

## Definition of Key Terms

### Artificial Intelligence/Machine Learning (AI/ML)

Artificial intelligence is the design, implementation, and use of programs, machines, and systems exhibiting human intelligence. Its most essential activities are knowledge representation, reasoning, and learning (Whitson, 2020).

### Computer Vision (CV)

Computer (or machine) vision is a capability that extracts information from 2D and 3D images (Hornberg, 2017).

### Convolutional Neural Network (CNN)

A CNN is an artificial neural network used in image recognition and processing domains (Nguyen, Huynh, Tran, & Ngo, 2019).

### Cyber-Physical Systems (CPS)

Cyber-Physical Systems are network-programmable devices that respond to digital messages through embedded capabilities (Aguida, Ouchani, & Benmalek, 2020). It is a subset of an Internet of Things (IoT) domain.

### Human activity recognition (HAR)

HAR is the process of identifying human behaviors from motion feeds (Gorgulu & Tasdelen, 2020).

### Internet of Things (IoT) device

The Internet of Things (IoT) attempts to widen the interconnectivity of computers by interconnecting objects (Commission of the European Communities, 2009).

### Motion capture (MoCap)

Motion capture is a process that digitizes structural body movements for film and television production (Gan, Li, Wang, & Zhang, 2020).

### Recurrent Neural Network (RNN)

An RNN is an artificial neural network used in sequential data sets like natural language processing and time series (Boorugu & Ramesh, 2020).

## Summary

The cost of healthcare is increasing, which creates the need for more automation. When patients cannot afford the required care, the quality decreases, or social programs must fund the difference. For many situations, like in-home monitoring of elderly and special needs patients, it is challenging to build that automation due to personal privacy and safety concerns. Researchers also encounter challenges spanning logistical, sufficient and diverse representation, and costs, among other entry barriers. After mitigating these issues, the research results are difficult and expensive to reproduce.

Implementing and verifying automation comes with a high barrier to entry, precisely due to personal privacy concerns, logistical complexity, ethical & cultural considerations, and procurement & configuration overhead. For example, a recent study shows that 95% of Pakistani versus 50% of New Zealand patients refuse to share a severe medical concern outside their primary care physician (Shirazi & Shekhani, 2021). Researchers create frameworks to mitigate these privacy concerns (e.g., redaction), though these procedures are challenging in practice (Blackhurn, 2021). Beyond human and process issues are technical complexities in configuring prototype autonomous assistants. It requires multiple domain specializations like computer networking, embedded technologies, AI/ML, and distributed computing (Tun, Madanian, & Mirza, 2021). Each cross-cutting concern adds complexity and reduces the probability that small teams can successfully provision their test environment. Furthermore, those difficulties limit other researchers from reproducing the results. These factors slow innovation and restrict the value researchers can contribute to the body of knowledge.

This study aims to remove these barriers using artificial agents within a simulation process. It implements these capabilities using open-source software and existing MoCAP recordings. Next, virtual patients inside a physics simulator will perform animation sequences under differential physical configurations (e.g., weight and height). The study attempts to show this approach for detecting falling behaviors in hemodialysis patients. It will use AI/ML and the CV algorithm’s ability to perform HAR tasks. The project scope is constrained to specific real medical needs, though it is more broadly applicable. For example, similar experiments could exist for monitoring child care. Regardless of the medical condition, the CV algorithm can learn HAR behaviors and then control CPS systems worldwide.

There are two research questions the study seeks to address. First, to what extent can the automation perform HAR tasks. Second, to what extent does automation perform in noisy environments. The experiments attempt to measure both aspects using the artifacts agents. Additional controls such as smoke and light levels will influence the scenes to increase noise for the virtual cameras. Using real humans, it would be challenging to safely and reliable test these environments. However, the study doesn’t attempt to prove that this approach is superior to traditional methods in the physical space.

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