**Using Artificial Intelligence/Machine Learning and simulation processes to improve elderly and special needs care**

Dissertation Proposal

Submitted to Northcentral University

School of Computer Science

in Partial Fulfillment of the

Requirements for the Degree of

DOCTOR OFPHILOSOPHY

by

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La Jolla, California

July 2022

Table of Contents

[Chapter 1: Introduction 1](#_Toc127014615)

[Statement of the Problem 2](#_Toc127014616)

[Purpose of the Study 3](#_Toc127014617)

[Introduction to Theoretical Framework 4](#_Toc127014618)

[Research Questions 6](#_Toc127014619)

[Significance of the Study 6](#_Toc127014620)

[Definition of Key Terms 7](#_Toc127014621)

[Summary 9](#_Toc127014622)

[Chapter 2: Literature Review 11](#_Toc127014623)

[Literature Search Strategies 11](#_Toc127014624)

[Theoretical Framework 13](#_Toc127014625)

[Challenges and opportunities for care providers 17](#_Toc127014626)

[What is the role of data mining 17](#_Toc127014627)

[What exactly is artificial intelligence 20](#_Toc127014628)

[How does computer vision work 22](#_Toc127014629)

[What’s the role of Markov chains 24](#_Toc127014630)

[How are neural networks evolving 30](#_Toc127014631)

[How does intelligent agent modeling work 33](#_Toc127014632)

[How does neural network training work 37](#_Toc127014633)

[What is autoencoding 47](#_Toc127014634)

[How does sequence analysis work 48](#_Toc127014635)

[How does recognizing human activities work 52](#_Toc127014636)

[How do dynamic environment simulations work 54](#_Toc127014637)

[Computer vision and autonomous driving 55](#_Toc127014638)

[How does the reproducibility crisis impact ML design 63](#_Toc127014639)

[Ethical considerations of AI 69](#_Toc127014640)

[Summary 75](#_Toc127014641)

[Chapter 3: Research Method 77](#_Toc127014642)

[Research Methodology and Design 77](#_Toc127014643)

[Population and Sample 78](#_Toc127014644)

[Instrumentation 80](#_Toc127014645)

[Study Procedures 80](#_Toc127014646)

[Data Analysis 84](#_Toc127014647)

[Assumptions 85](#_Toc127014648)

[Limitations 86](#_Toc127014649)

[Delimitations 86](#_Toc127014650)

[Ethical Assurances 87](#_Toc127014651)

[Summary 89](#_Toc127014652)

[References 91](#_Toc127014653)

**List of Tables**

[**Table 1** Design-science Guidelines (Hevner et al. 2004) 5](#_Toc117887981)

[**Table 2** *Survey search terms* 11](#_Toc117887982)

[**Table 3**  *Example Research Strategies for Classifying Movement in Video* 13](#_Toc117887983)

[**Table 4** *Activation Functions* 30](#_Toc117887984)

[**Table 5** *Principal Components* 33](#_Toc117887985)

[**Table 6** *Mean Time to Recover* 40](#_Toc117887986)

[**Table 7** *Example progressions of N.N. architecture complexity* 49](#_Toc117887987)

[**Table 8** *Ongoing Fees* 60](#_Toc117887988)

[**Table 9** *Threat Sources* 66](#_Toc117887989)

[**Table 10** *Alternative Research Approaches* 77](#_Toc117887990)

**List of Figures**

[**Figure 1** *Should you purchase more stocks model* 24](#_Toc117888007)

[**Figure 2** *n-gram Examples* 25](#_Toc117888008)

[**Figure 3** *3 GANN Architecture* 26](#_Toc117888009)

[**Figure 4** *TensorFlow Architecture for MNIST Analysis* 27](#_Toc117888010)

[**Figure 5** *Multi-dimensional convergence* 31](#_Toc117888011)

[**Figure 6** *BeeSmart Simulation* 34](#_Toc117888012)

[**Figure 7** *Genetic Algorithm Process* 35](#_Toc117888013)

[**Figure 8** *Multi-Region Deployment*  41](#_Toc117888014)

[**Figure 9** *Paxos Consensus* 42](#_Toc117888015)

[**Figure 10** *Durable Command Queue Pattern* 43](#_Toc117888016)

[**Figure 11** *On-device training architectures* 45](#_Toc117888017)

[**Figure 12** *Autoencoding architecture* 46](#_Toc117888018)

[**Figure 13** *NLP Analysis Procedure* 48](#_Toc117888019)

[**Figure 14** *Abstract Diagram of Differences* 49](#_Toc117888020)

[**Figure 15** *GAN Training Configuration* 51](#_Toc117888021)

[**Figure 16** *Network Structure* 53](#_Toc117888022)

[**Figure 17** *Taxonomy of Example Use-Cases* 54](#_Toc117888023)

[**Figure 18** *System Design* 55](#_Toc117888024)

[**Figure 19** *Training Configuration* 56](#_Toc117888025)

[**Figure 20** *Taxonomy of Participants and Example Challenges* 57](#_Toc117888026)

[**Figure 21** *Example Microservice Architecture* 59](#_Toc117888027)

[**Figure 22** *Preventative Maintenance System*  61](#_Toc117888028)

[**Figure 23** *Simulation Instance* 80](#_Toc117888029)

[**Figure 24** *Characters* 81](#_Toc117888030)

[**Figure 25** *Experiment Design* 82](#_Toc117888031)

# Chapter 1: Introduction

A demographic change will significantly pressure the global healthcare 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 et al., 2013). While these products provide incremental value, they do not move the needle. Nearly eight years later, the industry is driven myopically 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 (PDAs) (e.g., Amazon Alexa) to set reminders and record activities effectively (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 capitalize on the effectiveness and efficiency of autonomous assistants for the episodic falling syndrome (Blackhurn, 2021; Kim & Kim, 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, rural special needs communities in South Africa 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 et al., 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

The purpose of this constructive research study is to provide an understanding of the effectiveness and efficiency of autonomous assistants for episodic falling syndrome in elderly and special needs care organizations. Episodic falling syndrome patients have a high risk of falling and injury (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 to remove privacy and safety restrictions that would exist for real elderly and special needs patients. 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, 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 episodic falling syndrome 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 studying metadata properties like floor slickness and character overexertion (Aihara et al., 2021). In contrast, humanoids are well-suited for these experiments.

## Introduction to Theoretical Framework

The 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 (Bryar & Carr, 2021; Peffers et al., 2007). 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

In alignment with the purpose of this study, and adopts the following research questions:

### RQ1

What is the effectiveness of autonomous assistance for classifying behaviors of elderly and special needs patients for care organizations?

### RQ2

What is the efficiency of autonomous assistance for classifying behaviors of elderly and special needs patients for care organizations?

## 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 expands the knowledge body.

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

The research study uses the following terms throughout the dissertation. This section includes a summary of their definitions. See *Chapter 2: Literature Review* for more information.

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

Artificial intelligence is the design, implementation, and use of programs, machines, and systems exhibiting human intelligence. Its essential activities are knowledge representation, reasoning, and learning (Whitson, 2020). Practitioners use AI/ML processes to implement “fuzzy rules” that rely on statistical probabilities.

### Computer Vision (CV)

Computer (or machine) vision is a capability that extracts information from 2D and 3D images (Hornberg, 2017). CV processes can identify bounding boxes around objects, discover text, and classify facial behaviors, among other examples.

### Convolutional Neural Network (CNN)

A CNN is an artificial neural network in image recognition and processing domains (Nguyen et al., 2019). It mimics the biological structures of primate eyes by reducing image data through pooling actions. This process simplifies creating image masks for classification tasks.

### Cyber-Physical Systems (CPS)

Cyber-Physical Systems (CPS) are network-programmable devices that respond to digital messages through embedded capabilities (Aguida et al., 2020). It is a subset of an Internet of Things (IoT) domain. Practitioners use CPS to enable digital systems to interact with the physical world.

### Human activity recognition (HAR)

HAR processes identify human behaviors from motion feeds (Gorgulu & Tasdelen, 2020). It might assess several video frames and predict whether an actor is running, jumping, or sitting. These capabilities inform preventative and reactive controls to mitigate a situation. For instance, the process might detect a patient's fall and dispatch medical assistance.

### 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). It monitors and reacts to the physical world using sensors, motors, cameras, and similar devices.

### Motion capture (MoCap)

Motion capture is a process that digitizes structural body movements for film and television production (Gan et al., 2020). Practitioners attach tracking sensors to a physical actor’s critical joints and inflection points. Computer programs record and encode those relative changes for virtual digital skeletal movements resulting in those agents exhibiting natural behaviors.

### Recurrent Neural Network (RNN)

An RNN is an artificial neural network for sequential data sets like natural language processing and time series (Boorugu & Ramesh, 2020). HAR processes can combine CV and RNN to observe and predict workflows. For instance, CV can detect an agent’s performing a high-exertion activity and use that output as input to RNN for forecasting that person will injure themselves.

## Summary

Healthcare costs are 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 and cultural considerations, and procurement and configuration overhead. Researchers create frameworks to mitigate these privacy concerns (e.g., redaction), though these procedures are challenging in practice. 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. 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 episodic falling syndrome 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 childcare. Regardless of the medical condition, the CV algorithm can learn HAR behaviors and control CPS systems worldwide.

# Chapter 2: Literature Review

The problem to be addressed in this study is the inability of elderly and special needs care organizations to capitalize on the effectiveness and efficiency of autonomous assistants for the episodic falling syndrome (Blackhurn, 2021; Kim & Kim, 2021). This research theorizes that computer vision (CV) can provide a consistent experience across a diverse global audience. Building autonomous assistants is challenging due to requiring multiple domain specializations like computer networking, embedded technologies, AI/ML, and distributed computing (Tun et al., 2021). Beyond technical constraints, potential privacy and safety from video monitoring create barriers to locating volunteer patients. 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.

The purpose of this constructive research study is to provide an understanding of the effectiveness and efficiency of autonomous assistants for episodic falling syndrome in elderly and special needs care organizations. This research aims to deliver this capability by utilizing humanoid constructs within a realistic physics simulation process. Next, positioning virtual cameras, instruments, and devices within the virtual world enables researchers to collect their experimentation data. Lastly, automation can modify the environment using programmable interfaces such as raising the alarm or applying other mitigations.

## Literature Search Strategies

This literature review used the Northcentral University Library (NCUL) to identify relevant peer-reviewed articles and books published from 2019 to 2022. It also includes foundational papers for historical context and generally accepted process standards outside this period. Students use NCUL’s Roadrunner search to aggregate results from industry-standard sources like the IEEE Xplore Digital Library, ACM Digital Library, and ProQuest.

A breath-first search scanned for surveys, challenges, and opportunities on the constructive research project’s core concepts (see Table 1). The breath-first search uncovered several themes that drove depth-first investigations. For instance, researchers are approaching hyper-scale ML training with custom hardware acceleration and continuous learning-at-the-edge methods (Plus Company Updates, 2021; Prapas et al., 2021). In other cases, themes like *Using Convolutional-Graph Neural Networks (C-GNN) for HAR* necessitate a sequential breadth-first search to contextualize supporting concepts. This search process continued until finding fifty unique documents. Next, bibliographical reviews for each publication extracted themes. Those sorted themes are available in the proceeding conceptual frame section, which presents each topic’s current state and direction from Table 1.

**Table 2***Survey search terms*

|  |  |
| --- | --- |
| Concept | Example search queries |
| Elderly and special needs industry state | * (elderly care or special needs) and industry * (global or internal) and (disabled or medical) |
| Computer vision (CV) | * computer vision or CV * computer vision and (surveys or opportunities) |
| Human Activity Recognition (HAR) | * (human activity recognition or HAR) and (computer vision or CV) * HAR (state-of-the-art or challenges) |
| Machine Learning (ML) Training | * (ML or machine learning) training and scale * distributed ML training |
| Physics simulation | * (Unity or ROS or robotic operating system) and (process or environment) simulation * (dynamic or synthetic or virtual) environment testing |

This chapter aims to frame the historical drivers and crucial decisions that shape the state-of-the-art for AI/ML and CV sciences. It approaches the problem starting with a low-level view of data mining and neural network technologies. Then it examines shortcomings across those areas driving deep neural networks (DNN) as the defacto solution.

## Theoretical Framework

A theoretical framework is a blueprint that communicates a natural progression of the phenomenon to be studied (Dickson et al., 2018). It is essential for quality research as it outlines a systematic structure of definitions, concepts, and relationships. Four core approaches exist for studying a business use case or phenomenon (see Table 2). This study’s blueprint derives from a constructive design science research (DSR) methodology.

DSR is one of the most common research methods for information systems and technology (Silvestrini & Sammito, 2012). These studies identify a problem, build artifacts, and communicate the implementation’s unique value (Hevner et al., 2004). In addition, many researchers follow this process to build proof-of-concept and execute case studies. This methodology is appropriate for examining elderly and special needs care solutions. After creating the system, it can support a targeted case study that measures its ability to deliver value.

**Table 3**   
*Example Research Strategies for Classifying Movement in Video*

|  |  |  |
| --- | --- | --- |
| Approach | Description | Study Example |
| Quantitative | Studies the magnitude of a phenomena | Measure the resources necessary to classify movement with embedded systems |
| Qualitative | Explores a concept without a numerical basis | Exploration of reasons movement classification fails |
| Mixed-Method | Combines exploration and studying the magnitude of these issues | What preparation steps reduce the costs of movement classification |
| Constructive | Produce artifacts to study a scenario | Create an algorithm for classifying movements |

### Fundamental Approach

Constructive research practitioners gravitate toward either Design Science Research (DSR) or the Constructive Research Approach (CRA). One of the critical differences between them is that DSR relies more heavily on existing theories, versus CRA does not explicitly require a base theory (Piirainen & Gonzalez, 2013). More recently, Iivari (2020) criticized the debate stating that constructive research must first and foremost produce high-quality artifacts. She advocates for “less theory, but better design theory (pg. 504),” especially within rapidly evolving industries like Information Technology and Communication. Zeller (2014) would agree with this position, adding success criteria that the artifacts are “challenging, elegant and useful.” This research project aligns with these requirements by connecting artifacts with patient needs and challenges.

### Central Concepts and Relationships

Here, the study presumes that CV and HAR can improve the livelihood of elderly and special needs patients. However, implementing those custom models is prohibitively expensive, and any research conclusions will be challenging to reproduce. This research project aims to mitigate these challenges by demonstrating CV and HAR methodology with simulated humanoids. It is beyond the scope of this dissertation to prove those methods are superior to existing and more laborious strategies.

There are multiple core concepts necessary to deliver this outcome. First, a literature review must examine the challenges and opportunities for elderly and special needs care. Quality research starts from customer challenges and works backward to find technological solutions (Bryar & Carr, 2021). In contrast, technology-first methodologies have a higher risk of not producing valuable outcomes.

Second, the central premise relies on exhibiting CV and HAR methodologies for predicting actions and behaviors. Computer vision (CV) processes extract data from image sources. Next, human activity recognition (HAR) processes must classify that data into distinct actions and behaviors, such as the person sitting or falling. Those requirements raise several questions within the literature review context. For example, what mechanisms are being built or deprecated? This research study does not aim to create a novel solution and plans to reuse existing methods.

Third, the research topic must train the ML model using a simulated environment with humanoid characters and virtual instruments. This situation raises implementation questions, such as trade-offs between industry-standard tooling, design patterns, and configuration nuances. The literature review must identify strategies that are likely to produce high-quality results. It is beyond the scope of this dissertation to implement proof-of-concept (POC) solutions for every potential combination.

Fourth, the artifacts must be high-quality and functional within a noisy environment. Meeting these expectations raises questions regarding ML training strategies. For example, do other researchers remove (or add) randomness to their DNN architectures? Are there specific situations that are more applicable for improving model quality? This constructive research study aims to incorporate these recommendations but stops short of directly comparing algorithms or methods.

Fifth, the literature review must uncover strategies for scaling the ML training and inference to the production scale. This sub-topic is crucial for bringing ML capabilities to public markets. However, it is also sufficiently complicated to populate multiple separate dissertations. Therefore, this dissertation only discusses literature trends for high-performance hardware, low-power hardware, and edge processing.

### Implementations and alternative framework

The proposed framework establishes capabilities that align with the business challenge of improving elderly care and special needs. It uses generalizable virtual camera instruments for CV and HAR experimentation with humanoid agents. Aspects of this framework appear in other publications (Banjarey et al., 2021; Gu et al., 2021). However, utilizing humanoid subjects with HAR and CV is not mainstream in surveyed literature.

An evaluation of alternative conceptual frameworks also took place. First, would an alternative virtual instrument be more appropriate? Instead, this study could predict HAR with accelerometers and gyroscopes (Gu et al., 2021). Wearable sensors have several advantages, such as following the patient worldwide. Researchers have also demonstrated applying these sensors to predict diverse action spaces (Nugroho et al., 2018). However, CV-based agents can extract more context from those same behaviors. For instance, a biosensor can predict that the patient is eating but not the food type. Instead of directly competing technologies, future solutions must integrate these heterogeneous sources.

Second, an argument might exist that using humanoids is nonsensical and advocate for training the HAR models with public video repositories (e.g., YouTube). This approach has several benefits, such as realistic action depictions and freely available labeled data. However, training models on this real-world basis might be more challenging than the controlled and sterile simulation process. Furthermore, researchers can dynamically scale humanoid properties (e.g., weight) to assess model performance across parameter gradients. Future research could combine the frameworks with the video repositories validating the laboratory environment’s usefulness.

## Challenges and opportunities for care providers

This section is a placeholder for compiling notes from the Industry state section. It attempts to frame the business environment and limitations that require additional research.

## What is the role of data mining

The four data-mining categories are association rule mining, clustering, classification, and regression modeling (Barua & Mondal, 2019). Association rules are patterns like if *X, then Y,* such as a person buying bread (X) is likely to purchase butter (Y). Clustering and classification are related strategies that attempt to group similar items into buckets. The critical difference is that classification knows the bucket labels beforehand (supervised), while clustering does not (unsupervised). For instance, a teacher gives their class a quiz and then maps them into groups by their assessment score (e.g., A, B) is a classification problem. Suppose they mapped the students on their favorite color. In that case, the groups are not deterministic, which is a clustering scenario. Regression modeling tries to find a mathematical equation that explains the observations. A classic example estimates housing prices using square footage, house age, and room count, among other features.

Across these high-level categories, numerous scenario-specific algorithms are available for different data sets. For instance, Apriori-based algorithms rely on the concept that subsets of frequent itemsets must also be frequent item-sets to prune the search space and timely report recommendations (Mejia et al., 2017). Another use case comes from Self-Organizing Maps that cluster or categorize arbitrary data for anomaly detection (Sonmez et al., 2018). Then consider Ant Colony Optimization and Genetic Algorithms, which combine random guessing and regression modeling to iterate toward optimal solutions (Leios, 2017; Mirjaili et al., 2018). Other strategies exist to handle countless other challenges like dimension reduction (e.g., Principal Component Analysis) and brute force discovery (e.g., Parameter Sweeping) (Starmer, 2017).

### Organizational examples of data mining

Many financial investment firms rely on outcome-specific automated strategies to filter the sea of market data into a manageable number of options. For example, Fonskea and Liyange (2008) proposed a data mining strategy that tracks related companies' correlation (e.g., FedEx and UPS) and profits from deviations. In this case, both shipping companies will likely experience similar political and economic headwinds. Bhoopathi and Rama (2017) propose an Apriori-like algorithm that attempts to derive trading signals based on implicit associations between instruments (e.g., X and Y are inversely correlated). Hargreaves and Yi (2012) use a decision tree model to filter the Australian index on fundamental data (e.g., return on equity) from 2000 companies to a high-quality basket of the top six. Finally, George and Chang (2017) assessed the market interdependencies by transforming daily quotes into connected graphs.

### Explain challenges experienced using data mining

There is a joke that ‘70% of all statistics are made-up,’ inferring that the model is unlikely to work in practice without properly evaluating correlation versus causation. Carver (2007) explains that researchers focus on relevance, not “just seeing what we want to see.” Snee (2015) echoes that high-quality models are practical and explainable. Fonseka & Liyanage and George & Changat did not account for the contextually sensitive results of the Great Recession occurring in parallel. Bhoopathi and Rama’s association rules discovered tight relationships between Intuit (creator of TurboTax) and International Fragrance—with no economic justification. Aside from Hargreave and Yi, none of these approaches had a basis in modern market theory. For instance, correlations between price movements did not account for volume. The authors also limited their asset analysis to only primary assets instead of expanding into secondary assets. George & Changat determined that banks were the most critical aspect of their network but did not investigate interest rates, GDP, or consumer credit statistics. Bhoopathi and Rama could have transformed the data with a moving average to smooth out noise, decreasing false-positive rules.

### Enabling Machine Learning

Data mining enables transforming data into information. Researchers can build statistical models that predict outcomes when that information represents evidence for questions. Enabling this symbiosis requires well-defined objectives or machine learning algorithms will lead to inaccurate solutions.

## What exactly is artificial intelligence

Dreams of artificial intelligence can trace back to philosophical debates in ancient Greece. Prometheus would mold handfuls of clay into images of the gods and later give life. Ideas sprouted from mathematics, biology, and computer science before eventually producing modern artificial intelligence. While these different domains have unique perspectives, they collectively land in four categories of intelligent systems (Lukac et al., 2018). The first divide asks if the system *thinks* or *acts*, or more precisely, can reason about the problem. These top-level categories contain subcategories of applications that mimic *humans* versus *rational* actors.

### Description of Technology

There are three high-level categories of artificial intelligence: rules and heuristics, machine learning, and deep understanding (Buchanan, 2005).

1. Before 1962, applications would rely on practical techniques for reducing the trial-and-error search space. This heuristic-centric approach is helpful for chess and other video game engines. Despite criticism for being naïve, many LOB (Line of Business) applications continue to leverage this technique successfully.
2. In 1963, Edward Feigenbaum and Julian Feldman’s *Computers and Thought* centralized many ideas across the computing industry. Their literature and new programming paradigms, such as McCarthy’s LISP, laid the foundation that became machine learning. Researchers use these tools to build statistical models that represent a situation. For instance, what else could you recommend if a customer purchases bread? Perhaps butter, jam, and deli meat.
3. In 1949, neural scientists found that the human brain transmits signals between a weighted graph of neurons (Lukac et al., 2018). Despite unlocking the biological key to mimicking cognitive learning, the processing power was unavailable until the early 2000s. Researchers use neural networks to extract patterns for nebulous problems that meet or exceed human capacities.

### Purpose and Function

Traditional software follows the model of *data* plus *rules* equals *outcomes.* In contrast, intelligent systems use data and outcomes to derive rules. This distinction can be valuable when the *rules* are fuzzy or not entirely understood. After extracting those rules into a model, researchers, and engineering teams can predict actions across mechanical, thinking, and feeling tasks (Huang et al., 2019).

* *Mechanical tasks* are actions that are highly repetitive and benefit from automation. These are operations like turning on lights or assembly-line construction.
* *Thinking tasks* are operations that require analysis and rationalization. For instance, “does this picture contain a hotdog,” or “is this sentence grammatically correct?”
* *Feeling tasks*, emulating interpersonal experiences, and expressing empathy toward the users. These autonomous systems might replace a call center or control support chatbots.

### Evolution of the problem

Numerous organizations begin their journey into intelligent systems with statistical modeling and variance analysis. These approaches work for many linear models but break down non-parametric functions (Waal & Toit, 2011). For example, a business wants to appraise houses given a collection of features about the home. Houses come in all shapes and sizes, making it challenging to compare those features directly. Instead, the appraiser must approximate a function that considers these characteristics and their weighted importance. Meanwhile, another company must classify handwritten digits by mapping a 32x32 pixel image to its numeric value. Both scenarios and countless more require a mechanism to translate these non-parametric functions into parametric approximations.

### Nature’s solution

In biology, animal brains accomplish these tasks through meshes of neurons that transmit signals across connected synaptic (transforming) and activation (filtering) links (Keller et al., 2016). Later, that animal sees an object, and its brain encodes the image into a feature map. These features traverse the brain’s neural pathways and output a collection of responses, such as “the object is food and ten feet away.” Over time, the creature *learns* if those responses are correct and revise network weights to encourage or avoid similar situations. Data scientists and mathematicians replicate these ideas by calibrating edge weights, through backpropagation, on connected graphs called *neural networks*.

## How does computer vision work

Modern CV-based methods emulate primate biology across three distinct subsystems: neural dynamics, embodiment, and awareness (Ballard & Zhang, 2021). Researchers expand on these different subsystems to implement their specific use cases.

### Neural dynamics

Primates use retinotopy to map visual input from their retina to neurons. This process incorporates a random sampling and batching procedure to activate those neurons, with different combinations producing unique classifications. Marr (1982) proposed that machines could emulate this behavior to extract intrinsic images and functional constraints. His research shows that for every point within an image , it is possible to calculate its information level. Then, a smoothing function can remove the noise and produce object detection masks! Marr’s paradigm remains foundational to modern CV methodologies even forty years later.

### Embodiment

Bajcsy (1988) proposed that vision is an active process, and a hierarchy of decisions must occur. Each layer within the hierarchical map must encode the likelihood of a prediction within the context of the previous layer. For instance, when a person sees a cat, their brain uses different neuron groups to identify edges-to-shapes, shapes-to-labels, and aggregate labels to object names. Today, AI/ML practitioners call this construct the “hidden layers” within neural network architectures.

### Awareness

Around the mid-90s, researchers began exploring the notion of gaze control and fixation (Ballard & Zhang, 2021). They discovered that at least six separate systems stabilize objects within primate vision and implement a sophisticated data inventory system. For instance, when primates search for *a blue ball in the image*, their brains cache metadata to accelerate the gaze. Another critical service called fixation only persists memories with an associated high reward. For example, people safely drive to work without recognizing the preceding events because the routine operation did not produce new information.

In 1996, Kaelbling et al. proposed encoding these systems as policy maps that activate through an abstract reward function. Their notion of *reinforcement learning* explains how primates program their brain using visual information. Researchers have formalized this approach into a multi-process model where “reinforcement threads” combine to produce sophisticated composite decisions. Consider the problem of “should I eat this food?” In this situation, parallel threads predict it is a hotdog, hunger level, and availability of mustard. Their aggregate response invokes an appropriate behavior based on visual information.

## What’s the role of Markov chains

A core challenge to applying basic statistics to real-world data is assuming that each action is independent. However, many scenarios contain a conditional state transition probability dependent on the current state. If the stock market falls 5%, should an investor buy? The binary question requires a contextually sensitive answer considering their net position (short the market), outlook (2008 financial crisis versus 2017 Trump bump), and similar factors. Markov chains provide the mathematical basis for making statistical models incorporating these dependencies (Kahn Academy, 2014). The hypothetical purchasing model (see Figure 1) begins with a state diagram representing the available actions. Then Monte Carlo solutions can approximate each edge’s weight by random sampling and recording the decisions. At the same time, multiple use-cases can follow the same model, the scenario-specific decision weights. For instance, consider the differences between investing in (a) a 401k retirement account that only adds index funds versus (b) a delta-neutral (directionless) options trader. This trait is similar to other algorithms where efficient training requires relevant facts to specific questions.

**Figure 1**  
*Should you purchase more stocks model*

Diagram, schematic

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### Markov Experiment

Many online tutorials recommend exploring Markov chains as a solution to predict the next token in a sequence. Mason (2020) maintains an open-source repository of Shakespeare plays, which is easy to mine for different related sentences. An experiment began with downloading each script and normalizing the text into a corpus of lowercase words. Next, an iterator constructs a word\_dictionary that maps n-gram tuples to a word bag to the immediately following values. Then traversal of the Markov model chooses a random starting point, then selects a random next word, iterating until a stop condition. Across the test iterations, tests of different n-gram sizes (degrees of freedom) ranged from one to six. The higher the count, the more natural the sentences sound due to overfitting. Even at low n-gram terms, a frequent challenge arose from many unique words causing long sequences of static choices.

**Figure 2***n-gram Examples*Graphical user interface, text, application

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### Neural Networks

A Multi-Layer Perceptron (MLP) algorithm aims to map input features to a non-parametric function that approximates a set of outputs via an intermediary mapping function (the hidden layer). A fully connected graph can represent this structure. All inputs connect to the hidden layer, which connects to all outputs. Next, an iterative process forward-feeds examples through the network. Backpropagation updates the network weights and performs error corrections concerning the expected value (Ng, 2016).

According to Fridman (2017), backpropagation is a recursive process of taking the partial derivative of two logic gates and applying a weighted update. He expands on these connected graphs with an example of image classification passing through several layers (extracting edges, corners, object parts, and object identities). While the mathematical basis and engineering steps are somewhat procedural, the network architecture's efficient design requires art and science.

Perhaps the artfulness comes from a lack of planning or awareness of how the *ensemble* of distinct training subsystems combines. There is no reason to assume that every node is fully connected or has an edge weight above zero (see Figure 3). A logical representation might consider feature ‘x1’ connected to N neurons that regress one output, with feature ‘x2’ implementing some classification pattern. These network segments produce collaborative signals to provide a more productive inference about the broader topology. These network segment microstructures remain present in more complex architectures. The solutions by both BellKor (2007) and Li et al. (2019) suggest that this assumption is generally accurate.

**Figure 3**  
*3 GANN Architecture (de Waal & du Toit, 2011, p. 399)*Diagram

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### Neural Network Experiment

Consider the scenario of mapping 28x28 images of clothing to ten categorical labels (e.g., hats versus coats). The number of input features (neurons) is 784, and there will be ten output neurons—how many neurons should exist in the middle? Rosebrock (2019) provides an example solution (see Figure 4) to Fashion MNIST that begins with feature reduction through two max-pooling hidden layers and batch normalization. After cleaning, the solution uses a single 512-neuron hidden layer to predict one of ten output categories (with softmax). Reducing the hidden layer's size to 128 or 256 has minimal impact on the cross-validation scores, though shallow values of 5 to 16 negatively impact accuracy. In this example, changing the activation functions (e.g., softmax to tan-h) creates more performance fluctuation than any other knob, with model accuracy ranging from 20 to 85%.

**Figure 4**  
*TensorFlow Architecture for MNIST Analysis*Diagram, schematic

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### Observations

The first and most critical step in any data mining exercise is determining the question and discovering supporting evidence. Until this action occurs, the business is unlikely to have a successful deliverable and will spend excessive resources investigating irrelevant materials. After clearly articulating the business value, the engineer teams can perform broad filtration of data sources based on their ability to address those questions. During filtration, having a logical framework can improve the search process through partition pruning for the relevant data stores. For instance, if the business operates in Michigan, there is potentially minimal value in exploring Texas-specific data. After coalescing the supporting facts into a central location, cleaning and curation processes must confirm that the data is complete and pristine. Perfect information must be the right size and volume, or it might be incompatible with the analysis algorithms. For example, an instance learning algorithm expects individual records, not aggregate counts.

Markov Chains and Neural Networks are two strategies for making predictions on data through graph-like structures. Unlike basis statistics, Markov removes the need for independent actions and expresses them as weighted state machines. These state machines can improve workflow accuracy by guessing the next word in a sentence. Neural Networks and related MLP algorithms rely on weighted graphs and backpropagation to make predictions. While there is some artfulness, an alternative perspective asks if these are ensembles of small network segments. Evidence towards this interpretation exists in multiple advanced papers and helps to demystify the “machine learning black box.” It also means that several related concepts, patterns, and practices of data processing networks should also appear within more advanced neural network architectures.

## How are neural networks evolving

Frank Rosenblatt (1958) proposed the Mark I Perception as the first neural network architecture. This construct attempts to explain animals’ biological networks to *perceive* the world around them. The network consists of a collection of weighted sensors that converge into *one* learning circuit. Mechanical devices can replicate that implementation and train the connected weights to emulate animal intelligence with noisy data. Since this seminal paper, researchers have expanded deep neural networks to incorporate hundreds to thousands of connectivity layers. However, the specific configuration remains more art than science, with researchers manually iterating through trial-and-error experimentation (Ünal & Başçiftçi, 2021). The research field has two eras, with the first being the evolution of the artificial neural network (ANN) from 1989 to 2015. Then, the deep neural network (DNN) evolution became the primary focus from 2015 to the present. The industry is moving so fast that information beyond two years is becoming outdated.

### Artificial neural networks era

Perceptron was revolutionary, with its weighted signals triggering an activation function. This construct was insufficient for many scenarios and led to Multi-Layer Perceptron, which links a series of activation functions. Semantically, researchers can encode Boolean logic into these gates to derive more sophisticated insights. For instance, a network might contain two gates representing a person’s hunger level and food availability. Distinct signals can activate with each predicate to determine the overall scenario probability. That aggregate threshold can trigger an alarm or notification for the overarching decision to eat the food.

There are numerous activation functions, and a subset of the most common ones is available in Table 3. Originally researchers began with Sigmoid functions, which exponentially become a positive or negative one-value. However, this calculation is complex and slows down model convergence. A simple performance improvement came from using the tanh(x) function, similar to Sigmoid (Meta AI, n.a.). Now, researchers have chosen Rectified Linear Unit (ReLU) as the most preferred industry-standard algorithm (Ünal & Başçiftçi, 2021). Several scenario-specific variations like Leaky ReLU aim to scale and retain negative values versus truncating them entirely.

**Table 4***Activation Functions*

|  |  |  |
| --- | --- | --- |
| Activation Function | Formula | Description |
| Sigmoid |  | Mathematical function having an S-shaped curve with asymptotes at -1 and 1 |
| Tanh |  | A hyperbolic function that’s a ratio of sinh and cosh |
| ReLU |  | The most popular activation function |
| Leaky ReLU |  | An enhanced ReLU for incorporating scaled negative values |

### Architecture generalization challenge

Simple networks have poor learning abilities and are challenging to generalize to more sophisticated scenarios. Meanwhile, deep neural networks can learn intricate and subtle patterns but require more data before converging (Ünal & Başçiftçi, 2021). This trade-off causes many researchers to follow the principles of Occam’s Razor, which “promotes minimizing complexity and defending reductionism where possible (Oxford, 2022).” Calculating the most efficient and minimal network is an open problem, so researchers approximate with genetic algorithms. These algorithms aim to converge to a decent local optimum, not the global one. Genetic programming is an essential tool and recipient of significant scientific investment. Multiple dissertations could cover this topic, which is full of open problems.

Modern network architectures aim to simultaneously solve multiple objectives regarding weight and structural parameters to maximize fitness with minimal design (Ünal & Başçiftçi, 2021). Researchers can optimize various problem dimensions concurrently using ensemble methods, provided those subtasks have similar but not overlapping objectives (Kim & Cho, 2008). These subtasks typically mutate the network architecture through additive and pruning strategies until convergence, as illustrated in Figure 1.

**Figure 5**  
*Multi-dimensional convergence (Kim & Cho, 2008, p. 1605)*

Chart

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### Deep learning era

Object detection and labeling tasks were among the first problems leveraging deep neural networks. Notably, in 2006, separate work by Hinton and Li led to the creation of ImageNet, a CV model for detecting twenty thousand labels based on fourteen million images (Ünal & Başçiftçi, 2021). In 2012, AlexNet incorporated graphic processing units (GPUs), reducing the error rate by 50% over previous CV architectures. Today, using GPUs over CPUs is table stakes and has opened the door to training across big data sets.

DNN architectures contain multiple kernels, regularization, and hyperparameters. This variability makes them particularly challenging to optimize. Training hyperparameters control the model’s initial weights, learning rates, momentum factor, generalization, and the amount of training data (Jaisswal & Naik, 2021). These options influence several critical aspects of the final model, such as its sensitivity and degree of overfitting. Additionally, incorrect values can negatively impact training performance and defer model convergence.

Practitioners typically choose genetic programming or reinforcement learning (R.L.) for this procedure (Ünal & Başçiftçi, 2021). Data scientists can represent multiple expert systems as a connected mesh of R.L. models that search for ensemble methods, as Kim & Cho (2008) articulated. This mesh approach is standard for state-of-the-art architecture competitions like ImageNet Large Scale Visual Recognition Challenge (ILSVRC ).

## How does intelligent agent modeling work

Engineers consistently find that maintaining monolithic technologies requires substantial overhead. Alternatively, using microsystem architectures enables them to build and replace components rapidly in isolation. A similar idea exists with simulations that decompose the environment into multiple intelligent agents (see Table 4).

**Table 5***Principal Components*

|  |  |
| --- | --- |
| Aspect | Definition |
| Intelligence | The ability to reason about a problem |
| Simulation | An experiment that produces a statistical model |
| Environment | The universe contains the agents |
| Agent | An automaton that follows a predefined script |
| Objective | The goal of the agent |
| Tasks | The steps necessary to complete the objective |
| Notification | A collaborative or competing message between agents |
| Swarm | A group of agents |
| Choice | The random decision of an agent within its action space |
| Aggregate Choice | The net effect of multiple independent agent decisions |

A simulation experiment first identifies the environment, participants, and one or more objectives. Each participant, called an agent, attempts to complete their aim under guiding rules and principles. For instance, NetLogo’s BeeSmart environment contains multiple bees that try to maximize food production from various honey pots within a given scene (Wilensky, 2014). Initially, the swarm fumbles around until it discovers a food source. After some time, the colony will divide across multiple honey pots and compare site values with neighboring peers. Eventually, the bees converge to the optimal configuration that provides the maximum food for the hive.

**Figure 6**  
*BeeSmart Simulation (Wilensky, 2014)*

A screenshot of a computer

Description automatically generated with medium confidence

While no individual agent (bee) understands the ideal distribution across the environment, the aggregate of independent decisions enables analysts to extract sophisticated observations about the broader objectives. It is also possible to quickly expand upon this simulation by designing expert agents, such as communication specialists, that propagate messages twice as fast. After defining the role and its local rules, the existing simulation can immediately incorporate those customizations.

### Genetic Algorithms (G.A.)

The Traveling Salesman is a classical graph puzzle that attempts to find the most efficient route through N-cities. Even with ubiquitous access to cloud computing, enumerating through an exhaustive search is not practical due to the combinations growing at (Keller et al., 2016). As the simulation continues to scale out, it requires a mechanism to prune that search space and quickly discover the optimal answers. The Theory of Evolution states that biology weeds out inferior strains through the Natural Selection Process (Darwin, 1859). Computers can replicate this model through Genetic Algorithms to converge on optimal configurations (see Figure 2).

**Figure 7**  
*Genetic Algorithm Process*

Diagram

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The solution begins by modeling a potential answer as a vector of classification features. First, hundreds to thousands of randomly initialized instances run through the simulation to compute a per-instance score. Then a TOP-N ranking keeps the best instances, discarding the remainder. Next, a crossbreeding and mutation process mixes features from the fittest combinations to produce offspring. Those offspring cycle through this system thousands of times until only superior specimens remain.

### Multi-Level Agent-Based Modeling (ML-ABM)

After decomposing complex models into individual agents, a mechanism must aggregate the independent decisions into more macro observations. Cellular Automata (C.A.) paints this picture by grouping related swarms into “a hierarchical series of discrete systems (Makarenko & Osaulenko, 2018).” Through multiple levels of aggregation, agents can feed into swarms and those individual swarms into swarm networks.

For instance, a financial market environment has individual buy-and-sell participants who react to supply-and-demand fluctuations (see Figure 3). This example simulation contains thousands of personal portfolio accounts (agents) that frequently make rational transactions. An analysis could apply C.A. across these portfolios by aggregating many data points to improve the data’s usability for professional traders. However, an inefficiency exists within this design because some individual portfolios (agent states) are nearly identical. Like the risk-free rate, other aspects do not require the fidelity that swarms of agents produce. These situations can rely on ML-ABM to approximate irrelevant details (e.g., with caches) and enable fine-grained influence over critical decisions (e.g., with swarms of agents) (Hijorth et al., 2020).

## How does neural network training work

Model training aims to estimate the weights and connectivity structure for mapping a set of inputs to prediction outputs. This process requires optimizing a cost function using a series of forward-feeding data operations followed by backpropagation (Fridman, 2020). Backpropagation is a mathematical procedure that compares the expected versus actual outputs. Next, it calculates each parameter's partial derivatives and cascades updates to adjust the input weights accordingly (Lee & Yoo, 2021). Finally, after sufficient iterations, the network converges, which means that the difference between expected and actual outputs is within an acceptable margin of error.

### How are they scaling to millions of parameters

Recently, titans of the industry like Google Brain Team, OpenAI, and Uber Labs are scaling their evolutionary algorithms to millions of parameters without human intervention. Discovering the optimal architecture for CV and NLP problems at this scale is improbable due to its combinatorial nature and high costs per iteration (Lui et al., 2018). Instead, automation must represent the network as a traditional graph G consisting of nodes and weighted edges. Next, multi-level motifs augment the connectivity hierarchy to discover the impact of broad and narrow changes. For instance, these mutations might inject high-level filters or split the N-th hidden layer. In many ways, this is analogous to traditional fuzz testing, which exploits software through bit flipping.

Google DeepMind (2018) implements its search algorithm based on tournament selection. Each round begins by selecting the top 5% of the population and applying permutations from a discrete action space. After mutating the networks, only the superior offspring survive to the next round. This random search process is a genetic algorithm with an R.L. model steering its evolution to deliver the best of the breed through a simple search model.

### Modern scalability challenges

The sheer volume of matrix-based computations introduces challenges in scaling the training systems. Around 2012, researchers began using Graphical Processing Units (GPUs) over Central Processing Units (CPUs) to expedite model convergence significantly (Krizhevshy, Sutskever, & Hinton, 2012). According to some estimates, this hardware change leaped the state-of-the-art Deep Learning a decade (Ünal & Başçiftçi, 2021). However, researchers continue to require more extensive and sophisticated models. For example, GPT-3, an autoregressive language model, has over 175 billion parameters, a 10x increase over GPT-2 (Brown et al., 2020). More recently, Google Brain demonstrated an NLP translation model with over a trillion parameters (Fedus et al., 2022). This exponential parameter growth is likely to continue into the foreseeable future.

Several practical limitations exist to *scaling up* an individual server to support training a billion parameters. Instead, researchers turn to distributed systems patterns for horizontally *scaling-out* across hundreds to thousands of commodity servers (Langer, He, Rahayu, & Xue, 2020). The orchestrator, parameter server, and worker node are three essential roles within these compute clusters. Worker nodes communicate with the orchestration process to determine the next training operation in the queue. Then, it fetches the shared parameter state and performs its work. Eventually, the operation completes, and the calculated gradients push to the parameter server. The parameter server is responsible for merging worker node updates into the shared state. This cycle repeats until the orchestrator determines that no more work is necessary.

### Fault-tolerant design requirements

The exponential growth in parameters and data volumes forces the training process to execute for days or weeks. That process must be highly reliable to withstand random errors during this period.

**Influence of Hierarchy.** Generally speaking, two mechanisms for modeling distributed systems are lists and trees. *Lists* can efficiently manage small groups of related nodes; however, they can become cumbersome with more massive sets. *Trees* allow for more expansive designs as the system can hierarchically describe the problem through multiple levels of control. Consider the difference between Domain Name Services (DNS, tree) and NetBIOS (list). NetBIOS can easily manage a small branch office because the simple flat list structure is *globalized*. In contrast, DNS has multiple subdomains, each owned by heterogeneous service providers. Since each subdomain holds a specific set of children, read and write operations can be *localized*.

**Influence of Partitioning**. Localized designs are inherently more performant and fault-tolerant because of the containment of both scale and blast radius (Vosshall, 2018). Imagine a scientific dataset that has grown to several petabytes in size. The storage network would need to decompose this logical file system into multiple blocks and replicate it across multiple physical servers. These physical servers will run into mechanical failures, such as disk corruption or power outages.

When these outages occur, other nodes must efficiently Set up, Challenge, and Repair (SCR) the missing data (Chen & Curtmola, 2017). The time necessary to perform that repair operation is proportional to the size of each block and the system’s ability to scale the reconstruction over multiple peers horizontally. Assume that 1TB of the dataset has entered a failed state and needs to recover across a 10GB/s network (see Table 5). If only one virtual peer has a copy of the data, the system will heal in 102.4 seconds. Then contrast that with the smaller block size of 128GB, which can economically be sprawled across many servers, reaching an MTTR of under a second.

**Table 6**   
*Mean Time to Recover*

|  |  |  |  |
| --- | --- | --- | --- |
|  | Repair 1TB of Data | | |
| Block Size | Virtual Peers | Num Blocks | MTTR (seconds) |
| 1024 GB | 1 | 1024 | 102.4 |
| 8 | 1024 | 12.8 |
| 16 | 1024 | 6.4 |
| 512MB | 2 | 2048 | 51.2 |
| 16 | 2048 | 6.4 |
| 32 | 2048 | 3.2 |
| 256MB | 4 | 4096 | 25.6 |
| 32 | 4096 | 3.2 |
| 64 | 4096 | 1.6 |
| 128MB | 8 | 8192 | 12.8 |
| 64 | 8192 | 1.6 |
| 128 | 8192 | 0.8 |

**Influence of Fail-Over Groups.** Proxy servers and similar brokers operate on ephemeral requests and need fault tolerance from a different source. One strategy is maintaining a target group of service instances and monitoring their availability (see Figure 1). The monitoring can come from at least three reference points: (1) the network operating system, (2) the observed traffic of the broker itself, and (3) a local health agent on the service instance. The broker can use the Observed Health State Store (OHSS) to select the most appropriate receiver as new requests arrive. A recovery policy could also exist to manage any Service Level Objectives (SLO) of the backend application. For instance, if the backend application needs to be highly available, the broker could be augmented to trap specific exceptions and automatically route to another node. Other systems must optimize scenario-specific goals and metrics, such as more consistent response time, and choose completely different behaviors.

**Influence of Geo-Redundancy**. Cloud Service Providers (CSP) allow fault tolerance across multiple physical partitions (regions or availability zones). This design permits resiliency of entire data center failures without impacting uptime (see Figure 2). The scheme starts with deploying the service stack into two or more locations like Seattle and New York. Next, data store replication enables the sites to remain in sync. Finally, the user can discover the most performant service stack instance from a location-aware Canolical Naming Service (CNAME). That system can consider latency and other metrics, like the proposed Fail-Over Group solution.

**Figure 8**  
*Multi-Region Deployment*A picture containing text, map, table, indoor

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**Influence of Consensus.** The physical distance between the sites forces the need for eventual consistency protocols that range in complexity from (a) the latest timestamp wins, (b) Paxos algorithms, and (c) Byzantine General’s solutions (Zhao, 2014). The latest timestamp wins are easy to understand. Still, they must rely on highly reliable distributed clock synchronization, an open research problem (Ting et al., 2014). Under Paxos (see Figure 3), multiple rounds of preparation, acceptance, and learning phases occur to gain consensus. This elegant protocol can efficiently reconcile a single systems image, provided none of the nodes are malicious. If malicious or erroneous nodes exist, 3f +1 cross-validations must occur (Zhao, 2014).

**Figure 9***Paxos Consensus (Zhao, 2014, p. 196)*Diagram

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**Influence of Protocol.** Message passing between components can either use reliable or unreliable communication. Unreliable handoff can be helpful for best-effort or performance-critical systems, such as real-time video or sampled telemetry reporting. Reliable handoff is crucial for scenarios that mandate full and consistent accounting, such as user data or financial records. These fault tolerance decisions are not limited to the low-level transport protocol differences between User Datagram Protocol (UDP) and Transmission Control Protocol (TCP). They also appear at higher application levels (see Figure 4). The actor can notify the Alice service directly; however, the message could become lost due to a network failure. Instead, they can place the payload into a command queue and remove it only after the server-side acknowledgment. When Alice accepts the event, she needs confirmation from Bob and Charlie before returning success. Bob stores the event in a durable command queue, whereas Charlie executes it directly. In either scenario, the client can reliably infer that handoff has occurred.

**Figure 10**  
*Durable Command Queue Pattern*

Diagram

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### Scheduling-specific design requirements

The training process must also choose an asynchronous or synchronous scheduling architecture (Langer et al., 2020). Synchronous systems partition the training iteration (epoch) across the worker nodes and merge all responses before starting the next round. This approach has several advantages, such as simplicity regarding the design and maintenance. However, as the total worker nodes increase, so do the idle cycles from waiting on the slowest tasks to complete. Asynchronous systems aim to eliminate these idle cycles by prematurely starting the next training round. Since each worker node owns an isolated job, this technique is highly effective. However, the parameter server and orchestration processes must assume more complexity for this time-optimization. For instance, what should the parameter server do when task outputs (gradients) are late or never arrive?

Langer et al. (2020) propose a collection of boundary conditions for asynchronous architectures. For example, the parameter server system should disregard any gradient exceeding K-epochs latency or change an individual parameter by X-threshold delta. They also advise using priority queuing over FIFO queuing for the incoming responses. Another solution is to use multiple parameter servers and periodically reconcile the differences between their local states.

### Continuous learning techniques

Countless researchers and product teams periodically retrain their models from scratch as they iteratively add more example data. This approach is intuitive to design but wasteful and could become impractical as model parameter counts continue exponentially growing. Instead, researchers are proposing training architectures that support *continuous learning*.

**On-device training architectures.** On-device training architectures aim to fine-tune generalized machine-learning models using local sensor data (Lee & Yoo, 2021). This design begins with a cloud training process that consumes a public data set to produce a shared model. Next, a second training process will download and fine-tune the shared dataset to include personal data (e.g., a smartphone’s photo album). Lastly, an inference process uses the private model to deliver a personalized experience.

There are several essential advantages to this design pattern. First, the cloud-based training process does most calculations and has significantly more resources than an individual device. Next, the device-based training process can maintain data privacy and residency requirements because the personal data doesn’t need to be in the public data set. This characteristic could help overcome specific privacy concerns in regulated industries like healthcare. Third, the decoupled training processes refresh both models at a higher frequency.

**Figure 11**  
*On-device training architectures*  
Diagram

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**Stream-based training architectures.** This section is a placeholder for futureliterature review topics that may expand upon this point.

## What is autoencoding

In its simplest form, “an autoencoder learns the representation or code by trying to copy the input to the output by encoding the input’s distribution into a low-dimensional vector (Atienza, 2018, p. 78).” Figure 2 contains an example architecture illustration with three features compressed into one parameter before expanding into three new features. The precise connectivity graph depends on the specific situation. For instance, researchers can use this process for scenarios such as colorizing images, denoising, replicating artistic styles, and intrusion detection, among other conditions.

**Figure 12***Autoencoding architecture*

Diagram

Description automatically generated

### Example usages

Include a summary of the art stylizer paper

Include the summary of DACNN here from the intrusion detection paper.

## How does sequence analysis work

Natural Language Processing (NLP) sits at the intersection of artificial intelligence, human language, and computer science.

### Language Parsing

NLP systems typically begin with sentence normalization, combining and annotating tokens, and performing custom business logic (see Figure 13) (Edureka, 2018). Using Lemmatiziation and Stemming strategies enables the parsers to reduce sentence variability, such as removing verb-tensing. Next, subsystems like Named Entity Recognition (NER) associate annotations with the words that discover the sentence’s critical components. After chunking related tokens together, the scenario-specific business logic can operate on a semantic text representation. Depending on the use case, these steps could be massive subsystems or single lines of code.

**Figure 13***NLP Analysis Procedure*Diagram

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### Deep Learning

NLP appears across various use cases like language translation, speech-to-text, and sentiment analysis. In biology, animal brains accomplish these tasks through meshes of neurons that transmit signals across connected synaptic (transforming) and activation (filtering) links (Keller et al., 2016). Computer scientists mimic this behavior with Deep Learning on Neural Networks, essentially weighted graphs. Generally, NLP architectures use Recurrent Neural Network (RNN) structures containing connectivity loops to previous layers (see Figure 14). More advanced designs include subnets for memory retention (see Table 6), encoding and decoding segments, and greater parallelization from attention vectors (Fu, 2019). Researchers and engineers can add or remove these subsystems to optimize a specific use case.

**Table 7**  
*Example progressions of N.N. architecture complexity*

|  |  |
| --- | --- |
| Algorithm | Description |
| seq2seq | Simple Recurrent N.N. (RNN) for a token sequence to sequence prediction. These systems are easy to implement but lack memory |
| Long-Term Short-Term Memory | Extends the seq2seq by including a “long term” cache to hold context information |
| Transformers | State-of-the-art solution for massively parallel NLP through attention vectors and position encoding |

**Figure 14***Abstract Diagram of Differences*

Diagram

Description automatically generated

### Feature Extraction Process

The first steps to any business intelligence problem are identifying the specific questions and locating facts to support answers (Snee, 2015). When researchers ignore this preparation, it produces garbage-in/garbage-out results. For instance, Alsudias et al. (2014) built an NLP system for predicting where the user was during the submission (e.g., a restaurant or nightclub). Their approach extracts keywords from Yelp reviews (using term frequency), business metadata (e.g., name and location), and tweet metadata (e.g., timestamp). These features flow into a random forest classifier that determines the user’s location with a 74% accuracy. However, using only the business metadata produces an 88% accuracy, indicating that these additional details provide negative value.

Researchers might have specific requirements to model social media users’ speech patterns and create new content in their voices. The Feature Extraction Process must therefore consider the user’s metadata (e.g., age and locale), the online community properties (e.g., forum name), the posted content, and any quality ratings (e.g., Facebook Likes). There are several considerations to augment this process. For instance, adding a filtration step to remove comments with negative ratings might create more well-liked personalities. However, it could also be advantageous to generate trolls that argue an alternative position, reinforcing the political situation that the other side is illegitimate or less sophisticated.

### Training Process

Around 2014, GAN (Generative Adversarial) Networks became the state-of-the-art approach to producing high-quality fabricated content (Fridman, 2020). These systems utilize a feedback loop between a Generative N.N. (GNN) and Discriminator N.N. (DNN). Each iteration outputs a ‘Deep-Fake’ asset and assesses its likelihood of being legitimate. This process enables both systems to learn from one another, continuously improving. According to Fridman (2020), detecting Deep Fakes is an arms race because advances in DNN naturally improve GNN results. NPAC leverages this methodology for self-teaching its systems to deliver more accurate content (see Figure 4). The organization’s solution uses the NLP transformer to improve parallelization over LSTM and a second RNN classification network. Periodic snapshots archive the content and model state for offline troubleshooting use cases during training.

**Figure 15***GAN Training Configuration*Diagram, schematic

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## How does recognizing human activities work

One critical CV application is to detect human activities from photos, images, and video streams. This capability is essential for personalizing systems across the healthcare, smart home, and safety industries (Gu et al., 2021). Adapting traditional ML tactics to human activity recognition (HAR) is laborious, error-prone, and challenging. Researchers mitigate these issues with deep learning models (Banjarey et al., 2021; Gu et al., 2021). There are several algorithm families used to model these predictions.

### Restricted Boltzmann Machine (RBM)

The first HAR implementations used Deep Belief Networks as their prediction basis. Training this solution was extraordinarily challenging and deprecated (Gu et al., 2021).

### Convolutional Neural Networks (CNN)

The preceding section examined the biological constructs enabling primates’ vision and the solution of nature. A neural network consists of three building blocks' input, hidden, and output layers. For instance, an animal image classification system might assign 64x64 pixel images into ten predetermined categories. This example requires an input layer with 4096 neurons, an output layer of ten neurons, and some hidden layers in the middle. Adding more hidden layers enables extracting more details from the image, similar to object edges (layer-1), ears (layer-2), cat’s ears (layer-3), and a tiger’s ears (layer-4) (Fridman, 2017). While more complex networks can extract more insights, it comes with the cost of needing exponentially more data to train the model.

Experts suggest a fully trained model requires at least ten observations per parameter (Snee, 2015). This situation can become too expensive and require model compression strategies (Cheng, Wang, Zhou, & Zhang, 2018). For instance, the input layer could feed into a series of pooling transforms that downgrade the resolution by averaging every 2x2 pixels. Another tactic might focus on connecting and evaluating local segments of neurons before outputting into global join constructs and prognostication output (see Figure 16). Meanwhile, other situations, like estimating housing prices perform better with fully connected shallow pipelines. While standard architectures exist for many classes of predictions, some experimentation is necessary.

**Figure 16***Network Structure*

Diagram

Description automatically generated

## How do dynamic environment simulations work

This section is a placeholder for literature review material during the Unity versus ROS selection process. An initial proof-of-concept suggests that both solutions meet the requirements. Future investigation may be necessary during the fourth chapter

### Methods

This section reserves a placeholder for future investigation into best practices

### Unity-based

Placeholder for anything Unity-specific.

## Computer vision and autonomous driving

Researchers are applying CV to many health and safety systems like autonomous driving. Investigating these related use cases can uncover best practices and reusable patterns for elderly and special needs care.

Machine learning can enhance every aspect of the drive, from extending the physical parts’ lifespan to increasing the driver’s overall satisfaction. Figure 1 contains a non-exhaustive taxonomy of uses-cases for artificial intelligence in motor vehicles, such as reducing wear and tear and object detection. The central application topic is the primary deciding factor for item assignment within the tree. Many items, such as Voice Assistance (V.A.), could arguably live under a different pillar, safety. However, safety systems could use more traditional input interfaces in the same capacity, making this example fall under convenience.

**Figure 17**  
*Taxonomy of Example Use-Cases*

### Data collection process

Since covering each use case in full detail would fill multiple books, this section reviews these user scenarios’ commonalities. The lifeblood of these systems is data, and only through synthesizing information into knowledge can they be more adaptive. These processes require collecting telemetry, mining data, and modeling the interactions (see Figure 18). As simulations run across that model, statistical distributions form, leading to predictive capabilities. When the model’s complexity grows or the required accuracy increases, the learning system needs more examples to cover each scenario.

Consider the analogy of building an All-Wheel-Drive (AWD) feature that only knows about Florida’s flat tropical roads. Despite the engineers' best efforts, the vehicle will face challenges in Colorado’s ice-covered mountain climbs. Similar behaviors exist across the autonomous vehicle supply chain, demanding either (a) more data or (b) more erroneous assumptions. This trade-off introduces acceptable feature risks in specific situations (e.g., entertainment modules) and undesirable consequences for others (e.g., safety modules).

**Figure 18***System Design*

A picture containing text, map, indoor

Description automatically generated

Around 2014, GAN (Generative Adversarial Networks) became the state-of-the-art approach for constructing high-quality detectors and fabricated content (Fridman, 2020). These systems utilize a feedback loop between a Generative Neural Network (GNN) and Discriminator Neural Network (DNN). Each iteration outputs a ‘Deep-Fake’ asset and assesses its validity (see Figure 3). Under this process, both systems learn from one another, continuously improving their expertise.

**Figure 19**  
*Training Configuration*

Diagram

Description automatically generated

Automotive companies like Formula One use this methodology to synthesize more efficient race cars that can safely operate at high speeds (Smedley, 2019). First, a collection of features (e.g., car shape and weather data) load into the GNN and its simulation environment. Next, the output flows into a DNN, assessing the solution’s feasibility (e.g., wind drag and safety requirements). Then, the GNN modifies the solution’s parameters to search for a higher score (e.g., a faster car). After executing thousands of cycles, both networks converge with optimal solutions to deliver innovation (GNN) or detect problems (DNN).

### Safety Control Systems

Annually, 32,000 Americans die from automotive accidents, and another 2 million are injured (CDC, 2016). These statistics are unacceptably high and require innovations that increase all participants’ safety on the road (see Figure 20). Artificial intelligence can assist in these scenarios by collecting sensor data and predicting risks and opportunities. However, numerous open problems exist throughout the safety domain. These challenges should not discourage investments in these areas as they are essential to public safety.

**Figure 20**  
*Taxonomy of Participants and Example Challenges*

For example, manufacturers like Subaru and Lexus include audible collision alerts during lane changes or reversing. While these capabilities exist today, they are often incomplete models due to the high volume of edge cases, such as children fetching a ball from the street. Even after detecting the example child, several open problems span ethical and philosophical debates. Lex (2017) asksif avoiding the pedestrian requires killing the driver— what calculus dictates that autonomous decision? These situations might play out in fractions of a second, limiting the value of human intuition. Since concrete answers do not exist, machines must resort to static guardrails (e.g., slamming on the breaks or swerving) that could risk a multi-vehicle accident.

### Convenience Systems

Long monotonous segments are often necessary to arrive at the destination during a road trip. This requirement forces the driver to expel significant concentration relative to the mundane task. Instead, auto-pilot systems can take the wheel and allow the motorist to relax and participate in leisure activities (e.g., conversing with passengers). Some manufacturers tackle these needs with adaptive cruise control technologies. This approach is helpful in static environments (e.g., open highways) but encounters limitations in more dynamic environments (e.g., urban cities). Researchers are closing this gap by including more sensors that feed into sophisticated reinforcement learning algorithms (Fridman, 2020). However, continuing to scale these monolithic expert systems is challenging.

**Figure 21**  
*Example Microservice Architecture*

Diagram

Description automatically generated

V-TORCS (Virtual Open Racing Car Simulation) and other modern architectures address these issues using ensemble and multi-task learning methods (Li et al., 2019). Consider a decision process that feeds camera frames into an image classification Convolutional Neural Network (CNN) to extract objects and contextualize the environment (see Figure 21). CNN algorithms mimic an eye’s biological structures by normalizing neighboring pixel blocks to derive structure (Keller et al., 2016). These results flow into expert subsystems controlling the car, such as turning the wheel or accelerating. An ensemble of subsystem observations merges into a broader system-wide decision model that contains one or more I/O (Input/Output) controllers. Like other microsystem architectures, each subsystem’s implementation can evolve independently of peer components—enabling greater agility and innovation.

### Optimization Systems

Modern personal vehicles have a lifespan of over 200,000 miles and often travel 24,000 miles per year (Ford, 2012). Assuming a driver purchases a $25,000 car and keeps it that entire usable period, they will likely spend at least that much on fuel and repairs (see Table 7). Data scientists can improve this situation by introducing micro-optimization systems across the automobile. For instance, traditional cruise control maintains a specific speed (e.g., 70mph) without considering any environmental context. Meanwhile, a more intelligent system can factor in the road’s incline, the driver’s profile, and metrics about the trip to create a dynamic profile ranging from, e.g., 65-70mph. As this idea expands outward, it collects micro-optimizers that monitor all aspects of the driving experience, potentially saving hundreds of dollars in costs.

**Table 8**  
*Ongoing Fees*

|  |  |
| --- | --- |
| Line Item | Total |
| 200,000 miles @ 30 miles/gallon | 6,667 gallons |
| x $2.50/gallon | $16,700 |
| + Typical Repairs | $10,000 |
|  |  |
| Total Costs | $26,700 |

When the driver has advance notice that a component is likely to fail, they can schedule the maintenance and minimize costs. The Preventative Maintenance System (PMS) provides this capability by collecting component-level telemetry and looking for anomalous metrics (see Figure 4). For instance, an engine monitoring solution might observe the RPMs (Revolutions per Minute) and the electrical output. Sensor time series data are noisy and require a curation process (e.g., Kalman filter) to derive a stable moving average signal (Jackson & Rege, 2019). Next, the curated call flows into a Recurrent Neural Network (RNN), which uses sequences of previous tokens to predict future values (Keller et al., 2016). An anomaly exists when new observations deviate from these predictions and needs to surface in a decision-control process.

**Figure 22**  
*Preventative Maintenance System*Diagram, schematic

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### Smart City Integration

The future evolution of city planning makes urban areas highly connected with fast wireless networking and intelligent machines emitting enormous telemetry data volumes (Balduccini et al., 2018). The autonomous vehicle is a central participant in this ecosystem, as it transmits metrics to infrastructure (V2I) and other vehicles (V2V). These metadata feeds will enable more efficient traffic shaping, alertness to potential risks, and insights into driver patterns (Tong et al., 2019). For instance, each driver inputs their GPS destination and follows the route in an isolated silo. Tomorrow, aspects of those routing decisions can become centralized, resulting in less route congestion. While ideas of this ideal state are already coming to life in major cities like Seattle, Boston, and New York, the large-scale implementation is still years out (Cohen, 2013). Modernizing these areas will require significant infrastructure investments, consensus on V2X communication protocols, and machines implementing those standards. Machine learning technologies must synthesize those capabilities by making predictions by pairing vehicle-local sensors with ubiquitous cloud services.

### Observations

Three takeaways of this paper are (1) that artificial systems need to augment human processes; (2) a suitable starting place is safety and cost optimization; and (3) intelligent cities are several years away, requiring cloud services to fill that void.

The most powerful artificial intelligence applications use machines to enhance human capabilities rather than replace them. Motor vehicles contain many integration points. Machine learning can handle tedious aspects of the journey with greater precision and accuracy than humans. After freeing the driver from mundane work, she can focus on value-differentiating traveling qualities, such as talking with passengers and thinking about the day ahead. Meanwhile, intelligent systems remain vigilant in the background looking for risks like a child running into the road. Another collection of machine learning tasks revolves around cruise control capabilities. These systems keep us from harm’s way and reduce wear and tear on internal parts. Looking further into the future, integrating intelligent vehicles within smart cities promises more efficient traffic shaping and risk awareness. However, the necessary infrastructure investments will unlikely arise in the next decade. Instead, machine learning will pair vehicular telemetry with ubiquitous cloud computing to provide a similar experience.

## How does the reproducibility crisis impact ML design

There is an abundance of non-reproducible experiments because researchers do not account for nuances in the data collection (Rivera-Landos et al., 2021). These challenges originate from *Non-Determinism Introducing Factors* (NDIF), such as software updates and defects, hardware-specific differences, data uniqueness, randomization seeding, and dropout rates, among other reasons.

### Sources of Non-Determinism Introducing Factors

NDIF issues also originate from incorrect industry assumptions and unknown unknowns. For instance, software taint analysis is a process for discovering security-critical variables and parameters within an application. Generally, these tools parse the underlying bytecode through language-specific Reflection APIs. Next, they build call trees and use graph analysis methodologies to discover vulnerable code paths (Kilgallon et al., 2017). Researchers publish new techniques and present their findings using open-source products like FlowDroid, AmanDroid, and DroidSafe. However, the detection rate for those tools is highly dependent on configuration-specific settings (Qiu et al., 2018). This subtle dependency can be problematic for researchers and small businesses lacking the technical expertise to support multiple competing toolchains.

Recreating many foundational experiments is challenging and expensive, so researchers must assume that previous authors are correct. Unverified facts present a significant risk that can have cascading ramifications. Consider Majoranas, an extremely sensitive nanowire that operates at absolute zero temperatures and in extreme magnetic fields to measure individual electrons within quantum computers. This precision “plays an important role in protecting quantum information and enabling reliable computation (Langston, 2022).” Limited access to equipment forces many researchers to rely on computerized physics simulation processes. Recently, Pennsylvania State University could not reproduce several foundational studies and received opposite results (Frolov, 2021). After disproving basic expectations, researchers revisited other assumptions and found at least six false core tenants. This situation highlights the criticality of revalidating technological assumptions. The body of knowledge is never precise and continually evolves with new facts.

Negligence and maliciousness also create reproducibility challenges. Miyakawa has handled 180 manuscripts since early 2017 and identified 41 potentially fabricated experiments. When he requested raw for these studies, “more than 97% [(40 of 41)] pulled their publication request, suggesting a possibility that the data didn’t exist from the beginning (Miyakawa, 2020, p. 1).” The editor claims to spot these situations by looking for data too perfect, error rates improbable, and study impact too significant. Catching blatant lies is relatively easy though humans commonly only cheat a little (Ariely, 2009). Behavioral economists consistently demonstrate that people mispresent small details that lead to a better story with believably exaggerated results (e.g., an 75% accurate score becomes 82%).

### Influence of societal norms and ethical design

Hudson (2021) argues that researchers should focus on replicability over reproducibility. He identifies incorrect study design, not disproving the null hypothesis, wrong statistical methods, societal norms, and publication bias, among other factors. These factors impact research reproducibility. Therefore, researchers should accept that incorrect facts exist, and that’s because humans aim to prove what they believe. Douglas & Elliott (2022) responds to Hudson’s article, asserting it conflates value-ladenness with bias and mispresents values as evidential factors. They state that researchers are generally well-intentioned and aim to make reliable, repeatable studies. However, it is impractical for those practitioners to wait for results to be flawless, as this means science no longer evolves. Put another way, “all models are wrong, but some are useful (Denis, 2015, p. 3).” The quote infers that it can be challenging to include all aspects of the environment. These external factors can create deltas between expectations and reality. Academics should perceive the book of knowledge as continually developing principles and tenants, where more precise instruments will eventually supersede those ideas.

### Role of ethical design

Researchers need to manage ethical challenges that arise from their work. These issues originate from societal norms and internal biases. While several frameworks exist to guide the conversation, they can be ambiguous or focus on a subset of the problem.

Ethics are a system of moral principles that dictate the norms of a group. Societies implement these systems through social constructivism, enabling and constraining the group’s actions (Burr, 2015). Communities leverage this mechanism to assign truths and infer values about concepts (Gergen, 2010). Consider a project that seeks to prove that men are superior to women. Within a chauvinistic cohort, these results align with their worldview and are ethical. However, a diverse group would chastise the idea, regardless of methodology. Further complicating matters, moral identities are dynamic and evolve (or regress) over time.

Scholars need to understand their audience and the group’s customs. These social contracts limit the researcher’s influence and ability to solicit their work. These implicit rule sets vary between cohorts, making it impossible to remove these subtle biases entirely.

### Threats to validity

Four major categorical threats exist to making statistically accurate conclusions, leading to false, erroneous results (Parker, 1993). When designing high-quality experiments, the designers must be aware of these issues and their sources (see Table 1). Fundamentally, these challenges represent a degradation of the experiment’s confidentiality, integrity, and availability. These limitations prevent the generalization and reproducibility of research, resulting in the discrediting of publications and professional embarrassment (García-Pérez, 2012). Instead, researchers must decide on controls and procedures before even beginning data collection.

**Table 9***Threat Sources*

|  |  |
| --- | --- |
| Source | Description |
| Internal Threat | Contamination by the research team |
| External Threat | Contamination outside of the study’s controls |
| Statistical Conclusion Validity | Results are arbitrary or non-reproducible |
| Construct Validity | Controls are not enforceable or consistent |

For example, if a participant needs to provide personally sensitive information, the data collection must convey trustworthiness (construct validity). Otherwise, the candidate will likely hold back data like side effects that are highly relevant to the research project. Without trust, the contributor might engage in activities that directly contradict the study (external threats). The research team might lack plans to deal with these confounding variables and deviate arbitrarily from excluding group members (internal threats). Since these results are now arbitrary, shoehorning outcomes into various statistical models until it lines up (statistical conclusion validity). An unlimited number of these permutations exist, and removing every situation is impossible (Parker, 1993). However, any procedure that reduces the influence of garbage-in/garbage-out experimentation is ideal.

### Internal biases

Researchers need to understand their internal biases. Everyone has historical and cultural defaults that lead to prejudices. These subtle classification differences influence language and construct our reality (Owen, 2017). Words matter, and one needs to choose them carefully. These biases sneak into our written and verbal communication, and they cause us to gloss over Diversity, Equity, and Inclusion (DEI) issues. For instance, the terms such as whitelist and blacklist have racial connotations. These modifiers become a sub-conscience reinforcement that one’s worldview is the only perspective.

### Sources of ethical frameworks

Numerous professional, regulatory, and advisory groups create frameworks that outline strategies for approaching ethical designs. These professional standards can contain conflicts of interest, hidden agendas, and inconsistent moral standards (Tan, 2021). The Belmont Report (1979) famously defines three core principles: respect for persons, beneficence, and justice. These tenants ask researchers to treat everyone fairly and avoid harm. However, even this simple statement has ambiguity.

After forty years, the ethical code requires modernization to align with evolving worldviews. Adashi et al. (2018, p. 1347) argue that the Belmont Report’s “distinction between research and practice is disappearing within the commercialization of present-day research.” Businesses actively debate the definition of “harm” and propose a notion of “harm versus setback.” This worldview states that any action that is not directly harmful is, at worse, an indirect setback. Roberts (2021, p. 15) proposes that researchers “must focus on risks of the research process itself, not outcome-related risks as downstream consequences are beyond the purview of ethical gatekeeping.” Facebook has a moral (and potentially legal) mandate to protect its user’s privacy. Under Robert’s definition, the social media juggernaut can ethically track relationships between billions of people. However, it is not bound to prevent malicious auxiliary use cases (e.g., election interference). While this position resonates with specific cohorts, it faces fierce opposition from others.

### Controversial Subjects

Many academic and business communities embrace Diversity, Equity, and Inclusion (DEI) concepts. These ideas are becoming mainstream, and that will cause them to become shared truths and social norms. Researchers that fight against this force are likely to find exclusion and isolation (Adashi et al., 2018; Owen, 2017). Instead, they should adopt social standards and assume “people are people.” However, this is often easier said than done. Human data sets contain numerous highly correlated variables (e.g., race and income). These statical properties prevent merely dropping an individual column and making the results racially neutral. Researchers can explicitly call out the risk in their findings, but fully addressing this situation is an open problem.

## Ethical considerations of AI

Artificial intelligence is a scary black box that spreads malicious propaganda, destroys jobs, and seeks to destabilize honest citizens’ values. This statement is intentionally farcical, yet it also touches on fundamental concerns of ethical AI designs. People fear what they do not understand and use science fiction to fill these gaps. Within those futuristic worlds, machines become the dominant species that control every decision of an enslaved human population. However, several challenges prevent this transition of power from becoming a reality, such as intelligent systems that lack actual *intelligence* (Hole & Ahmad, 2019; Upchurch, 2018; Wildberger, 1996). Instead, organizations must assess these tools rationally, explore applications that enhance human capabilities, and remove undifferentiating overhead.

### Roles of Artificial Intelligence

Despite artificial intelligence already being well-entrenched in everyday life, there are concerns about its role. First, does the advancement of machine learning mean fewer jobs? Second, of those remaining jobs, are humans giving away control unnecessarily? Third, are those machines capable of manipulating the public to steal dominion?

**Role in Employment.** Before 1949, digging a ditch would take hours or even days with a crew of manual workers. After the invention of the backhoe, these jobs required less time with fewer employees. From the organization’s perspective, these efficiencies translate into faster time to market at lower costs. Meanwhile, the former diggers became displaced into new roles, repairing, operating, and supervising the machinery. Each of these positions requires entire supply chains of support. For instance, it takes factories to produce the backhoe parts, each staffed with hundreds of blue-collar jobs. Cities must also build universities and technical schools to train team members to fill these roles, expanding the job market.

Similarly, modern businesses actively seek methods to reduce costs and improve efficiencies through automation. The most powerful artificial intelligence applications use machines to enhance human capabilities rather than replace them (Boire, 2017; Heer, 2019). For instance, a person can write a more profound business case than a machine; however, the same device will have fewer grammatical errors. This dichotomy exists because humans specialize in contextualizing thought versus using patterns to make predictions (Scheler et al., 2019). Many professions exist as a combination of decision-making, pattern recognition, and mechanical tasks. Expert systems address specific job requirements; however, superseding the soft skills that unify these role components is challenging (Huang et al., 2019).

Specific low-skilled jobs, such as bank tellers and office clerical staff, are at risk of being replaced (Hamid et al., 2017). Similarly, expert pattern-matching tasks like identifying tumors in MRI (Magnetic Resonance Imaging) becomes commoditized through AI systems. Given the lower entry barrier, some low-skilled workers will transition to better-paying jobs operating sophisticated and commoditized systems. For instance, many workers cannot access foreign markets due to language and communication limitations. Artificial intelligence can aid these in these translation scenarios while leaving control with humans.

**Role in Decision Making.** Many decision-making processes can benefit from machines providing recommendations and validations. For instance, a court judge could use an intelligent system to assess how their sentencing aligns with existing norms. Perhaps the device predicts the defendant should receive five years of probation, while a judge considers fifteen years in prison. When the validation check expresses such a difference in opinions, it could suggest that unconscious bias is taking place and warrants additional considerations. That bias either provides ammunition for appeals processes or incarcerates people unjustifiably long.

While this approach has much potential, there are concerns that professionals arbitrarily accept recommendations. However, these challenges occur everywhere automation controls the ‘last mile’ of decision-making. If the suggestion comes from a machine or peer, the person in charge of the process must be accountable for the final call. Blindly delegating control to machines is dangerous because learning algorithms are greedy, brittle, rigid, and opaque (Hole & Ahmad, 2019). Until artificial brains can rationalize abstract thought, humans must perform this task.

**Role in Manipulation.** Modern censorship does not restrict free speech; instead, it increases the noise and drowns the signal (Thomas, 2019). Fundamentally, marketing campaigns and propaganda machines follow the same process of Segmentation, Targeting, and Positioning (STP) (Kane, 2019). Delivering on this objective requires pattern matching, content delivery, and human intuition. Automation is well-suited for these tasks and can use social media channels, like Facebook and Twitter, to connect with billions of people and manage significant portions of those interactions.

Congressional and media sources raise ethical questions about the ease of access to these capabilities for political manipulation. Unfortunately, these questions are mostly talking points rather than a call for action. Artificial intelligence has many abstract concepts that do not fit within the complex and opaque legal language (Guiffrida et al., 2018). For instance, machines cannot reason about their instructions, so can the courts hold *them* accountable? Perhaps the system designers should be responsible for their creations. However, the algorithms are primarily algebraic formulas controlled by end-users. Without a mechanism to define and enforce a standard operating behavior, it is impossible to expect a different outcome.

### Design Considerations

Two recent attempts to define this process for ensuring ethical AI are the European Union’s Ethics Guidelines for Trustworthy AI and the OECD’s Principals of Ethical AI (E.U., 2019; OECD, 2019). Both documents describe the need for artificially intelligent systems to be human-centric, transparent, explainable, robust, and secure.

### Human-Centric

Robotics’s Three Laws state that automation should not injure humans ignore people’s commands, and protect their existence (Asimov, 1942). These rules lay a foundation for the idea that devices exist to cooperate and enhance humanity. Unfortunately, the machines cannot reason and are bound to their program designs. Since machines cannot devise these criteria independently, it becomes the system engineers’ responsibility to enforce these requirements. Those decisions are predominately a matter of business priorities and vary across different use cases. For instance, a military weapons designer like Lockheed Martin views its human-centric role as protecting American interests at foreign nations’ expense. This perspective is radically different from other organizations yet equally valid.

### Transparent and Explainable

Artificial brains often rely on deep learning techniques through neural network solutions. These networks approximate a function that maps inputs and outputs through multiple non-parametric transforms. While data scientists can perform experiments to verify the model’s accuracy, they often cannot explain it (Gilpin et al., 2018). This limitation prevents broader adoption in places like the European Union, where the General Data Protection Regulation (GDPR) grants citizens a Right to Explanation.

Further complicating matters, neural networks learn the patterns we *ask*, not necessarily the ones we *mean*. For instance, Beauty.ai, an algorithm for rating female attractiveness, lost credibility due to only giving high scores to light-skinned candidates (Upchurch, 2018). This outcome was not intentionally malicious but the byproduct of not sufficiently representing minorities in the training set. Similar imbalanced issues occur across many real-world domains and require sophisticated data-handling strategies (Kaur et al., 2019). Even with expert data scientists, missing these edge cases and producing invalid predictions is possible.

### Robust and Secure

Engineers who become data scientists follow a different curriculum than their peers who become security specialists. This distinction in training is most evident in the lack of controls across artificially intelligent solutions (Lin et al., 2018; Sethi & Kantardzic, 2018). Malicious actors can influence these predicted decisions by inserting erroneous samples into the training set or directly attacking the probability distributions. For instance, researchers have shown that applying tiny amounts of distortion to images can change the graphic’s predicted class (e.g., cat versus dog) (Sethi & Kantardzic, 2018). If people cannot trust the classification algorithms’ integrity, how can mission-critical environments effectively use them?

### Observations

Artificial intelligence is a tool that can automate mechanical tasks, pattern-match data, and enhance human capabilities. Organizations can use these means to improve efficiency and reduce wastefulness. These innovations deprecate the need for specific skill sets and lower the entry barrier into other expert systems. While this causes an initial decrease in jobs necessary, entirely new industries follow shortly afterward. This promotion justifies the short-term pain when a society can replace low-paying jobs with high-paying alternatives.

Machine learning technology is too immature to delegate business-critical decisions. Instead, professionals should consider these technologies for initial recommendations and verify that their choices are free of unconscious biases. For example, a court judge should assess their sentencing aligning with a regression algorithm’s prediction and not blindly issue that verdict. Humans must maintain control of our actions and consequences. However, preventing machines from manipulating our free will can be challenging.

Laws cannot keep up with technology’s high-velocity innovation, causing businesses to define and self-regulate their ethical behavior. This moral desire must compete against existing business priorities without an official solution for maintaining accountability. Those priorities will vary significantly between organizations, as defining ‘human-centric systems’ is ambiguous. Moving past those challenges are issues with the fundamental integrity of neural network technologies. Implementing transparency and explainability are open research problems for all but the most trivial systems. After solving those issues, ensuring only inclusive training data use requires significant investments into unverifiable results.

These limitations bring the discussion around full circle to the beginning. Artificial intelligent systems are not ethical, evil, or corrupt. They are tools that automate everyday tasks and lower the barrier to entry. Users of that tool must know what these predictions mean and how they influence decisions. However, that is not the same thing as delegating control with impunity.

## Summary

This chapter contains the study’s literature review on modern AI/ML concepts. It began with foundational concepts like data mining and multi-level perceptron techniques that form the statistical basis for CV. These statistical models aim to emulate biological structures found in primates. However, primates have very sophisticated subsystems for embodiment and awareness that grant them contextually sensitive information beyond these simple models. Researchers use reinforcement learning to approximate Markov chains as decision policies. This technique has enabled machines to solve more complex use cases than ever.

Next, the deep learning era utilizes ubiquitous access to cloud resources and specialized hardware. Researchers can train models with nearly one trillion parameters to gain extreme predictions for challenging problems like natural language processing. They approach these state-of-the-art designs by assembling multiple reinforcement algorithms to mutate the model’s architecture. Like traditional generic algorithms, these expert systems cross-breed random model network connectivity until they discover the most efficient combinations.

There are several significant ramifications to this evolution. For instance, the computing resources necessary for training are growing exponentially, but the per-unit capacity is linearly increasing. This situation means that ML training must operate in highly distributed runtimes. Failures are likely to occur within these environments, and the orchestration system must account for error conditions. Consider the influence of discrete processors merging calculated gradients and the impact of network latencies. The processors began with relatively similar policy maps, mutated with an ensemble of RL updates, and must reconcile the changes. One could quickly fill several dissertations on this topic alone.

Third, this chapter examines the reproducibility crisis and ethical considerations arising from these steps’ sheer complexity. AI/ML is a tool for enhancing productivity, and humans must remain aware that biases will creep into the design. These issues stem from systemic data correlations that are not always obvious (e.g., race and income). Controls and procedures must limit these factors and promote explainable AI.

# Chapter 3: Research Method

The problem to be addressed in this study is the inability of elderly and special needs care organizations to capitalize on the effectiveness and efficiency of autonomous assistants for the episodic falling syndrome (Blackhurn, 2021; Kim & Kim, 2021). This constructive research study aims to provide an understanding of the effectiveness and efficiency of autonomous assistants for episodic falling syndrome in elderly and special needs care organizations. Episodic falling syndrome patients have a high risk of falling and injury (Shirai et al., 2021). Like other projects, a high-quality research effort begins with a well-defined plan and stated outcomes. This chapter aims to meet these requirements by detailing the research methodology and its appropriateness. Next, it documents mechanisms for collecting data and analyzing that information. The chapter concludes by enumerating known assumptions, limitations, delimitations, and ethical assurances.

## Research Methodology and Design

Design science is a research methodology that creates and uses purposeful artifacts 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 (Bryar & Carr, 2021; Peffers et al., 2007). The methodology comes with well-defined guidelines 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.

Many people erroneously believe one method is superior to another (Creswell, 2014; Jason & Glenwick, 2016; McCusker & Gunaydin, 2015). Instead, researchers must align the method with the research problem and purpose. Design science is appropriate for understanding the effectiveness and efficiency of autonomous assistants for episodic falling syndrome in elderly and special needs care organizations. The study considered and declined alternative quantitative, qualitative, and mixed methods. These approaches best align with problem and purpose statement variations (see Table 10). Suppose the objective is to compare treatment effectiveness or aggregate patient monitoring implementations. In that case, respectably, quantitative and qualitative methods are a better fit.

**Table 10**  
*Alternative Research Approaches*

|  |  |  |
| --- | --- | --- |
| Approach | Description | Example Use Case |
| Quantitative | Statistical modeling of a scenario | * Estimate the probability of an event * Stating a broad generalization * Cause and effect analysis |
| Qualitative | Non-numerical representation of a scenario | * Open-ended surveys * Exploration of needs * Investigating a local issue |
| Mixed-Method | Combination of both quantitative and qualitative | * Examining the breadth and depth of a topic * Examining a scientific idea and then mapping it to use cases |

## Population and Sample

This study focuses on elderly and special needs patients at risk of falls and injuries. That population is large, with some estimates claiming over three million hospitalized accidents annually in the US alone (Centers for Disease Control and Prevention, 2020). These persons can fall due to "risk factors that are both intrinsic (physical and psychological) and extrinsic (related to environmental safety)(Lytra et al., 2022).” For example, a fall could be the byproduct of weight, mobility impairments, cognitive load, medications, lighting, floor sleekness, and tiredness, among other reasons. The software can generate each discrete combination of these situations, which, in this research, equals the study population.

Testing a nearly unlimited combination of patient characteristics and fall risks would be impractical. Instead, a sampling procedure that combines MoCAP sequences with different physical properties in a noisy simulated world is required. The most common place for patients to fall is the bedroom or bathroom (65% and 20% of total falls, respectively)(Aihara et al., 2021). Therefore, the sampling will consider everyday actions within these environments, like getting into bed, bathing, and dressing.

For the study to succeed, it needs sufficient *power* to measure the *effect* in question. Several parameters control the power of an experiment, such as relaxing the confidence interval, using parametric statistics, converting to a one-tail model, increasing the samples, or adjusting the sensitivity (Donovan, 2016). Effect size measures the strength of a phenomenon (Donovan, 2016). Calculating the difference between the two distributions is relatively straightforward and can be determined beforehand. The study uses an iterative sequential sampling policy instead of a fixed size upfront (García-Pérez, 2012). In this situation, that would mean first choosing two similar virtual agent populations (e.g., age of 50 and 200LB weight) and comparing *noise level* and *HAR prediction accuracy* as independent variables. The study’s design has the flexibility to simulate sufficient combinations for an appropriate sample size.

This study assumes a target effect size of 0.3. G\*Power version 3.1.9.7 projects that t-tests of the “difference between two independent means (two groups)” for a one-tail model will need 111 simulation runs to measure a 0.95 power with 95% confidence. Since the available MoCAP sequences and simulator configuration options are virtually unlimited, there should be sufficient coverage of the problem space. Therefore, a high probability exists that adequate data production can occur to represent the phenomenon realistically.

## Instrumentation

The study has three aspects that require data collection: ML training performance, model accuracy, and inference performance. This information originates from the Amazon SageMaker and AWS RoboMaker services (AWS, 2021), which offer these capabilities through their “bring your own container” design. Researchers essentially bundle custom automation and open-source tooling into a virtualized process. SageMaker uses public cloud resources like computing and storage to execute the experiment hundreds or thousands of times. It also integrates into TensorFlow 2 for collecting accuracy and performance metrics. These features reduce the complexity of building boilerplate instruments for many standard requirements. RoboMaker simplifies building agent simulations using the Robot Operating System (ROS) ecosystems.

These tools and services offer built-in consumable metrics using extensive developer tools such as Amazon CloudWatch and TensorBoard (AWS, 2021; TensorFlow, n.d.). The underlying services support custom metrics for investigating model efficiency. Implementing custom metrics beyond troubleshooting scenarios is beyond this project's scope.

## Study Procedures

The study uses AWS RoboMaker’s WorldForge to create three simulation worlds representing studio, 2-bedroom, and 2-level homes (see Figure 23). This feature offers parameterized controls to introduce variations like floor plans, furnishings, and environmental changes (e.g., ambiance)(AWS, 2020). While WorldForge can quickly produce dozens or hundreds of unique worlds, this offering is beyond the project’s scope. Instead, having one static instance of each world type is appropriate because only 111 total test cases are necessary for the sampling requirements.

**Figure 23**  
*Simulation Instance*

Diagram

Description automatically generated

Adobe Mixamo is an open-source repository containing 2500 MoCAP animations and 145 characters. The study will choose three characters and five behaviors as a subset from this collection and utilize them across multiple test cases with varying placement options (see Figure 24). During the behavior simulation, statically placed virtual cameras will capture the animation sequences and broadcast them as RGB+D video feeds. The video input streams into Amazon SageMake, which aims to predict which behavior has occurred.

**Figure 24**  
*Characters*



A machine learning algorithm will process short video clips and predict agents’ intent based on their behavior. The algorithm models the subject’s skeleton movement changes into a sequence-to-classification model.

This process begins with sampling the video stream from 24 frames per second (fps) to 6 fps. This operation aims to speed up model convergence and reduce operational costs. Next, similar to Das et al. (2019), the research will use the OpenPose library to identify the character’s joint positions in a given frame. Those matrix-encoded positions represent the input sequence to the model. According to the literature review, these matrices should be relative delta updates, not literal coordinates. Third, the matrices feed into an RNN-based algorithm (e.g., LTSM) for sequence analysis. This portion will use the standard Keras libraries for generating TensorFlow, a neural network. Lastly, a fully-connected layer extends the architecture to represent the classification action space and output.

This experiment repeats enough test case combinations for the sampling requirements, with each iteration archiving the video feeds, world configurations, and model accuracy scores (see Figure 25). A feedback monitoring process will ensure adequate behavior coverage and identify potential gaps. An example scenario is the patient falls behind the couch or another obstructed view.

**Figure 25**  
*Experiment Design*



ROS simplifies initiating character behaviors through configuration rules (see Figure 25). For example, the world definition might load the Alice model at a specific offset. Next, wait for several milliseconds before performing a particular motion capture file. Suppose that motion causes Alice to walk into a couch. In that case, the physics engine will prevent her from traversing through solid matter.

An explicit assumption is that training the model to detect motion-capture falls and similar behaviors implies the ability to observe episodic falling syndrome falls. This assumption is reasonable because the study looks for patterns in skeletal movements. It would be possible to validate this assumption using freely available videos from Reddit and YouTube channels. However, confirming this point is beyond the study’s scope.

## Data Analysis

There are two phases to implementing an AI/ML process: training the model and operationalizing the capability. The analysis must confirm that these phases meet acceptable quality standards. Additionally, it must address the research questions from Chapter 1.

This research project attempts to demonstrate extracting *intents* from dynamic and noisy video streams (see RQ1). A measure of the inference accuracy and the extent to which the scene contains noise must exist. Unity offers several rendering effects for smoke, fog, reflections, and lighting. Controls exist to adjust these effects and their enablement strength between zero and one hundred percent. This analysis is appropriate as it assesses the research questions directly.

Tensor Flow 2 generates statistical information regarding the model training performance. These Key Performance Indicators (KPIs) describe gradient convergence, model accuracy, and various troubleshooting metrics. An analysis must confirm that the training configuration occurs efficiently. Suppose the performance is substandard. In that case, this research plans to investigate the defects and reconfigure the training service (e.g., Amazon SageMaker). It is beyond this study’s scope to create “a perfect model” and only seeks to demonstrate the research technique’s viability. However, this study will validate that training is reliable and reproducible across positive and negative test cases.

An analysis of the model inference must confirm that it is usable. This phase requires provisioning a model endpoint and posting experimental data. A simple approach could be using RGB+D cameras to record a small human group repeating the humanoid behaviors. There are several core advantages to this solution. First, it demonstrates bringing the simulation process into the real world. Next, these volunteers are readily available through work and social gatherings. It is beyond this study’s scope to “perfectly predict” every behavior. Instead, the goal is to collect and evaluate operationalizing the research technique.

## Assumptions

Researchers must be conscious of the internal and external factors influencing their studies. Making an assumptions inventory is essential to quality research because it communicates the implicit drivers in the design. There is an assumption in this research that open-source motion capture (MoCAP) files are compatible with industry-standard physics simulation processes. The test cases aim to use virtual cameras to capture this information in 3-D open worlds. Suppose it is not possible to reuse that footage. In that case, the study can flatten the MoCAP to 2-D and present the findings. This approach is not as impressive but would complete the dissertation requirements.

The current plan also assumes access to a highly discounted rate for cloud computing resources. Amazon Web Services (AWS) has several programs for aiding researchers, like AWS Cloud Credit for Research and AWS Educate. Presently this study has funding through one or more of these programs and can pursue the entire project’s scope. Suppose that Amazon discontinued funding. In that case, the study would reduce the scale and focus on fewer test cases and humanoid configuration combinations.

This study makes several assumptions about the current industry state. It assumes that mainstream solutions like Amazon SageMaker, Robotic Operating System, Docker, OpenAI’s Gym, and Unity’s PhysX deliver the capabilities necessary to build the core artifacts. This situation would allow the experiment to focus on the AI/ML components, not rewriting boilerplate infrastructure. Suppose the toolsets haven’t matured to an acceptable level. In that case, the study will simplify the training subsystem. Similarly, these can be simplifications for hosting ML inference endpoints if they are overly cumbersome.

The implicit assumption is that virtual agents can substitute humans in semantically similar configurations. It’s beyond this project’s scope to evaluate the validity of that assumption. Future research could exist to compare real cameras against the MoCAP footage.

## Limitations

Limitations are internal and external factors that *implicitly* restrict the study from exploring all aspects of the problem. The previously stated assumptions also act as limitations. This subset would include technical feasibility, continued resource access, and real-world application.

This study aims to build a HAR classification model that supports a predefined set of activities due to challenges in finding sufficient example data. In this case, expanding the sample to contain open-source repositories will become necessary. These repositories could include YouTube, among other sites.

## Delimitations

Deliminiations are internal and external factors that *explicitly* restrict the study from exploring all aspects of the problem. Humanoid actors initialize with a configuration that controls their mechanical movement. There are virtually unlimited permutations for these characters and their weight, height, agility, and flexibility, among other properties. The distributed training process must set value bounds to learn the problem space efficiently. For instance, there’s only one person over 635 kg weight (Guinness World Records, 2022). Therefore, it does not make sense for test cases to exceed this extreme limit. Similar practical constraints also exist for other properties. It is beyond the scope and budget of this study to examine outliers.

This study utilizes video footage from simulated resources that might behave differently than physical beings. These distinctions arise from software errors, hardware resources, and modeling errors within the underlying data. HAR is also a vast concept with virtually unlimited permutations. The research project aims to minimize these challenges within the existing simulation software’s capabilities.

## Ethical Assurances

Northcentral University’s Institutional Review Board (IRB) must issue a statement covering ethical concerns, privacy violations, or undue harm risks. This study does not involve human or animal participants; in this respect, it meets the IRB requirements by default. The research utilizes computer simulations, which doesn’t raise privacy or ethical concerns.

This study uses humanoids in a physics simulation process as a research technique that mitigates ethical concerns and personal privacy risks. Since a humanoid is a virtual construct, it intentionally and explicitly divorces any moral hazards. Furthermore, the simulation has no right or assumption of privacy, as it does not exist in the real world. To verify the model training, a small cohort of volunteers will re-enact safe behaviors that do not risk personal privacy or harm. For instance, the falling behavior can be on a padded surface.

Medical facilities have a business requirement to collect private information from patients. While building a system that stores and retrieves this data is relatively trivial, several specific considerations influence the final implementation. Which users can issue queries against the datastore? What maintains the confidentiality of these records? How will auditing and compliance reporting work? Does this data have legal or regulatory implications? Answering these questions produces a model of acceptable risks and identifies business policies requiring cybersecurity enforcement. These enforcements protect the business against negligent and malicious attacks that could harm the integrity or reputation of the brand.

The principal objective of any business is to execute its mission in the most efficient manner possible. Delivering on that mission requires choosing between acceptable risks and desirable conveniences (Mickens, 2018; Dai Zovi, 2019). For instance, many small to midsized business owners lack the expertise to run a domain controller or email service. Employing dedicated staff retracts from resources that could provide value differentiation towards its core competencies. Contracting a consulting firm would be less expensive but lacks the deep economy of scale discounts available from Microsoft Office365. While financial factors influence many decisions, the security and compliance teams must assess the privacy and availability risks. Not all decisions originate from the leadership and often from internal department requests. For instance, a data science team might require a Juypter Notebook server with access to a production database. While that team has enough knowledge to be dangerous and deploy an operational instance, they might lack a broader understanding of business continuity requirements (Brown, 2015). What physical host controls this instance? Does the database connection use encryption? How are backup and restore scenarios handled? Until understanding these subtle decisions, it is impossible to determine if a failed server hard drive will lose three minutes or years of productivity.

These decisions must influence the study’s data storage design to be secure, reliable, and durable. In this context, the *seed* data is not confidential and comes from public repositories. However, there are risks that the *result* data can become corrupted or destroyed. That situation would risk the dissertation process completing on time. This constructive research project mitigates those scenarios using automated backup into Amazon Simple Scalable Storage (S3) storage and frequent commits to GitHub. Both services offer industry-standard durability, versioning capabilities, encryption at rest, and authentication controls.

The researcher is responsible for building the artifacts, measuring their accuracy, and reporting the results. There is the potential for biases impacting the study due to resource constraints. For instance, the project might plan four MoCAP sequences but only three work successfully. In that case, the results should not ignore the failure and instead discuss potential reasons for the issue. It is beyond this project’s scope to validate every situation though it should make reasonable attempts. Additionally, controls are in place to limit cheating or deceiving the results. For example, the result data originates through an automated process.

## Summary

The problem to be addressed in this study is the inability of elderly and special needs care organizations to capitalize on the effectiveness and efficiency of autonomous assistants for the episodic falling syndrome. These challenges exist because it’s difficult for researchers to experiment within personal private space. This study aims to mitigate those issues using a virtual environment and humanoid characters that perform MoCAP animation sequences. There are unlimited permutations the agents could perform. This study scopes the action space to 117 behaviors, prioritizing the most common situations and use cases.

The study uses industry-standard tools (e.g., AWS RoboMaker and Amazon SageMaker) to build a human activity recognition (HAR) computer vision (CV) model. Those tools include built-in instruments and metrics for assessing the machine-learning process's performance, quality, and efficiency. The study procedure will generate randomized worlds for the characters to move around and utilize virtual cameras to monitor their behaviors. Next, a data analysis phase will validate that the HAR model can reliably extract intents (RQ1) and the process's efficiency (RQ2).

Numerous assumptions and delimitations influence this project. First, that modeling HAR is possible within the virtual environment. Another hypothesis is that this approach is even a practical research method. Delimitations are necessary due vast combinatorial set of behaviors. Examining every potential aspect of this problem is impossible, so prioritization is essential. Lastly, the study lacks ethical or privacy concerns because all agents are virtual.

# Chapter 4: Findings

The problem to be addressed in this study is the inability of elderly and special needs care organizations to capitalize on the effectiveness and efficiency of autonomous assistants (Blackhurn, 2021; Kim & Kim, 2021). These situations have a high barrier to entry in studying due to technical constraints, limitations in reproducing results, and privacy and safety concerns. This constructive research study aims to provide an understanding of the effectiveness and efficiency of autonomous assistants in elderly and special needs care scenarios. It delivers this capability by modeling human movements within labeled video recordings by tracking the subject’s skeletal movements.

This chapter outlines the experiment’s findings and answers to the research questions. Specifically, this study aims to understand the following two aspects of autonomous assistant effectiveness and efficiency:

1. What is the effectiveness of autonomous assistants for classifying behaviors of elderly and special needs patients for care organizations?
2. What is the effectiveness of autonomous assistants for classifying behaviors of elderly and special needs patients for care organizations?

## Trustworthiness of the Data

The dissertation proposal outlined a research strategy that relies on Adobe’s Maximo MoCAP database. During the initial experimentation phase, this approach was determined to be impractical because the character’s movements were too artificial and ridged. As a result, the study’s human activity recognition (HAR) classification model would reliably predict the *character*, not the *behavior.*

The experiment mitigated this issue by adopting the kinetics 700-2020 data set from DeepMind (Smaria et al., 2020). Kinetics is a large-scale, high-quality collection of 650,000 YouTube video clips that cover sixty-five thousand human action classes. Humans manually annotated ten-second segments with single action classes such as playing instruments, shaking hands, and jumping. Alphabet, the parent company of DeepMind and Google, has vetted the labeling accuracy through “comprehensive statistics that baseline the results using the I3D network (Smaria et al., 2020)”. Additionally, independent verification of the data set’s label accuracy occurred in at least twenty-two publications, such as Zhu et al. (2021) and Orhan (2021).

The kinetics dataset has four core advantages: credibility, transferability, dependability, and confirmability. This study’s results are more credible because they must align with existing publications or have a strong justification. The dataset also gains transferability due to its usage of real-world people. Each action class has at least seven hundred examples, improving the predictions’ dependability. Lastly, the results are more confirmable because external parties choose the videos, limiting the researcher’s ability to insert biases.

## Results

The kinetics-700 training dataset contains 530,510 YouTube videos that third-party users have uploaded. This research effort successfully downloaded 424,613 (80%) of the potential dataset totaling 9.7TB in size. The primary reason for missing the remaining 105,897 (20%) was due to network timeouts and without retries enabled. Since the missing videos follow a random distribution across seven hundred categories, it is unnecessary to reattempt their collection (see Table 11, Appendix 1).

**Table 11***Processed Video Category Statistics*

|  |  |
| --- | --- |
| Statistic | Value |
| Total Categories | 700 |
| Minimum Videos Per Category | 250 |
| Maximum Videos Per Category | 881 |
| Standard Deviation Videos Per Category | 128 |
| Median Videos Per Category | 611 |
| 95th Percentile Videos Per Category | 838 |
| 99th Percentile Videos Per Category | 860 |

**Figure 26***High-Level Analysis Process*

The kinetics-700 annotations specify the offset (in seconds) and duration of the labeled action within the video. A high-level illustration of this analysis is available in Figure 26. This research project used the OpenCV library to sample one frame every half-second during that period for a maximum of 20 frames/video. The sampling process persisted those frames into Amazon S3, an object store, and queued them for Carnegie Mellon’s OpenPose framework (Cao, Hidalgo, Simon, S, & Sheikh, 2021). Amazon Elastic Container Service (ECS) scheduled the library operations across 38 x p4gdn.xlarge instances for 49 hours (152 VCPU, 608GiB RAM, and 38 NVIDIA T4 GPUs).

The OpenPose framework inferred millions of potential human poses within the frame as lists of 25x3 matrics. Each item represents a likely body and the location of its twenty-five body parts (see Figure 27). The framework reports body part locations as the three-part tuple X, Y, and confidence score. OpenPose doesn’t provide any consistent list order guarantees of potential humans detected. For instance, the first frame might report Alice, Bob, and Charlie – versus the second reports Bob, Charlie, and Alice. A heuristic algorithm compared the relative movement distance of skeletons across frames to provide consistent sorting (see git://src/extract/tracer.py).

Next, a normalization and annotation process assessed the motion sequences. This process began with encoding the motion sequences into Nx25x3 matrics, where *N* represents the subsequent half-second frames. Since videos originate in different resolutions and frame sizes, the body part locations’ X&Y-coordinates became regularized from absolute pixel offsets into relative distances between zero and one. This step aims to enable motion sequence comparability across discrete videos. Amazon Rekognition, a computer vision service, further annotated the frames with object, activity, and facial detection metadata.

Lastly, aggregation queries assess the information extracted from the videos and attempt to answer the original research questions. Specifically, what are the effectiveness and efficiency of autonomous agents in assisting elderly and special needs care facilities? This research project hypothesizes that monitoring human activity recognition (HAR) enables these agents to make informed decisions and reduce the overhead of care facilities. Suppose that quality can improve and simultaneously costs decrease. In that case, one expects that the accessibility of those services should increase due to commoditization. That, in turn, improves medical care for an aging population.

**Figure 27***Pose Output Format Body-25*

A picture containing diagram

Description automatically generated

Provide an overview of the demographic information collected. It can be presented in a table. Ensure no potentially identifying information is reported.

### RQ1

*What is the effectiveness of autonomous assistants for classifying behaviors of elderly and special needs patients for care organizations?*

The OpenPose framework offers a foundational capability to extract skeletal positions from a 2-D frame. This constructive design research project extended core features to support monitoring human activity movements across multiple subsequent images. It can classify those sequences into coarse behavioral categories, not necessarily the seven hundred labels. For instance, *playing cello* and *playing clarinet* are distinct labels. However, the actor is typically sitting in a chair and only moving their hands slightly. Likewise, the movement similarity score for *eating donuts* and *playing the flute* was too close to distinguish for many videos.

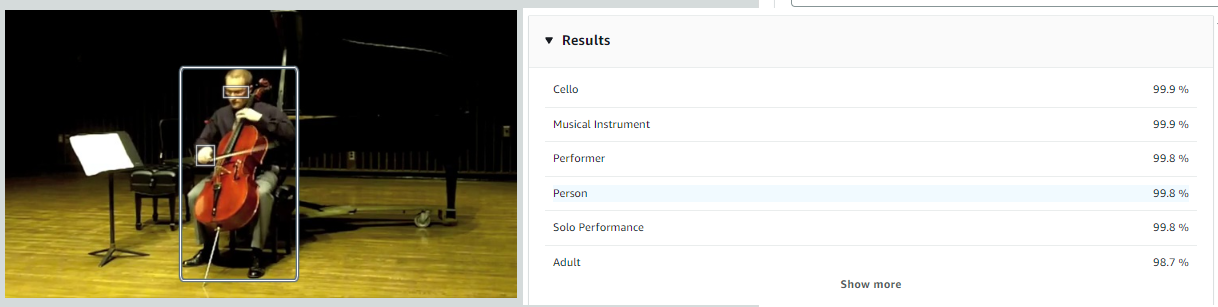
**Figure 28***Playing the cello (-23ykna85DI)*

A picture containing text, yellow, different

Description automatically generated

Using full-body skeletal monitoring is also insufficient for several kinetic-700 action types. For instance, videos within the categories of *waving* and *washing hands* focus the camera on only the person’s hands. This situation causes OpenPose not to detect other body parts and return a low-confidence 25x3 position matrix. Carnegie Mellon’s team has addressed this situation with two purpose-built models for faces and hands. The research examined these features briefly and found them inconsistent with arbitrary video feeds. These challenges were more pronounced in low-resolution cellphone recordings due to blurry motion. Actors routinely rotate their orientation relative to the camera, which causes the OpenPose framework to predict phantom limbs.

**Figure 29***Cello with label annotations*



Requiring more information than simple skeletal movements was expected and called out during the literature review (see Chapter 2). The research project increased accuracy by adding object detection metadata to the frames. For example, their body posture would infer that the person is sitting in a chair and labels for the *instrument* and *cello* detections within the frame. Calculating the likelihood of the person using the object was straightforward, using collision detection with the human’s and object’s bounding boxes. While this methodology was broadly effective, it didn’t work with perspective shots. For instance, if the cello were near the camera, its bounding box would saturate the frame and trigger the collision logic.

### RQ2

*What is the efficiency of autonomous assistance for classifying behaviors of elderly and special needs patients for care organizations?*

An underlying assumption of this research project is autonomous assistance can monitor the person in their home and replace nursing staff with electronics. These video recording devices have unfiltered access to the patient’s privacy and data security. This situation makes it ideal for the analysis to occur on-premises and never leave the local network. Additionally, this design improves the system’s reliability by removing remote dependencies. However, it also means that the system must have high efficiency to perform these operations using commodity hardware.

The Amazon ECS cluster processed 4.2 million seconds of video during the experiment using 6.7 million compute seconds. All code within the cluster emits telemetry to AWS X-Ray, a distributed tracing solution. These traces report that processing a high-resolution (1080p) clip takes 9.67 seconds, with 86% of the time spent waiting on network I/O (checkpointing frames). Suppose a reduction or elimination of these checkpoints occurred. In that case, the entire data set could reprocess in 0.94 million compute seconds. There are further potential performance gains from multi-threaded extraction processes. This outcome means the approach is sufficiently efficient before any optimizations.

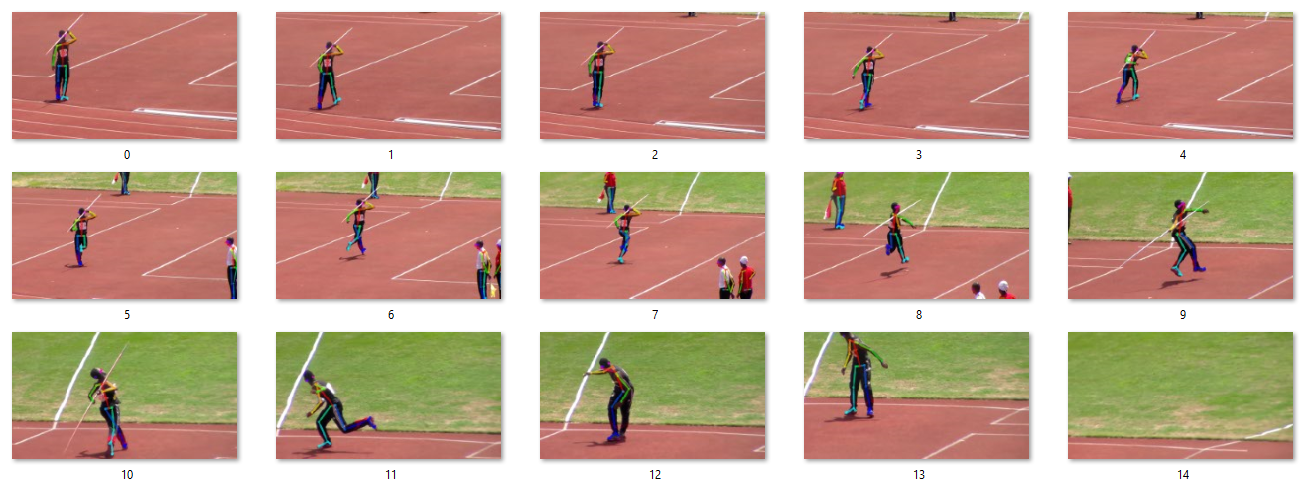
## Evaluation of the Findings

This constructive design research project demonstrates that it’s possible to classify human activity using their skeletal movements. It also provides evidence that an arbitrary activity taxonomy could exist through ensemble methods that combine additional metadata sources. Entrepreneurs can also package these solutions onto commoditized hardware and know sufficient processing power exists to keep data local and secure.

These findings align with recent state-of-the-art publications and classical theory. For instance, Ballard & Zhang (2021) states that primate vision relies on a hierarchical system of understanding and that system layers annotations to derive deeper insights. Likewise, this research found many indoor activities have a high similarity score. Das et al. (2016) enumerate challenges to HAR predictions within indoor environments. However, the authors only report that the datasets are not widely available. After completing this project, the limited availability is partially due to many categories being too similar. For example, one sits in their chair to eat, watch tv, defecate, and read a book. These situations share a partner action of *sitting,* and the derived behavior becomes apparent only through annotations.

In contrast, outdoor activities are more expressive and form discrete signatures (see Figure 30). The first five frames are the composite activity of *holding something* and *standing*. Then in frames seven through thirteen, the entire body rotation is an entirely different activity.

**Figure 30**  
*Javelin Throwing (zVlBFLFkUNk)*



## Summary

*Summarize the key points presented in the chapter.*

# Chapter 5: Implications, Recommendations, and Conclusions

The problem to be addressed in this study is the inability of elderly and special needs care organizations to capitalize on the effectiveness and efficiency of autonomous assistants (Blackhurn, 2021; Kim & Kim, 2021). These situations have a high barrier to entry in studying due to technical constraints, limitations in reproducing results, and privacy and safety concerns. This constructive research study aims to provide an understanding of the effectiveness and efficiency of autonomous assistants in elderly and special needs care scenarios. It delivers this capability by modeling human movements within labeled video recordings.

Design science is a research methodology that creates and uses purposeful artifacts 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 (Bryar & Carr, 2021; Peffers et al., 2007). The methodology comes with well-defined guidelines 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.

This study employed this methodology by building a computer vision (CV) algorithm that makes human activity recognition (HAR) predictions by monitoring the subject’s skeletal movements. It obtained this information using Carnage Mellon’s OpenPose framework, which detects the position of twenty-five skeletal markers during the video sequence. Example markers include the subject’s head, left elbow, right knee, and pelvis. The people move at different rates within the video clips, such as Alice jumping at the one-second offset versus Bob waiting until the third second to start. Dynamic time warp (DTW)-based clustering similar to Zhang et al. (2021) sufficiently minimized these speed variabilities. DTW provided two foundational characteristics. First, it programmatically aligns key-frames within the sequence and simplifies comparing two skeletal behaviors. Second, it produces a distance value for clustering the behaviors using the standard k-nearest neighbors (k-NN) algorithm.

This chapter examines *Chapter 4 Findings*’ implications of RQ1 and RQ2 being sufficiently efficient and effective. It also frames recommendations for practice and future research efforts. Finally, the chapter concludes the research study with its final call to action and take-home message.

## Implications

Begin writing here…

Checklist:

Organize the discussion around each research question and (when appropriate) hypothesis individually. Support all the conclusions with one or more findings from the study.

Discuss any factors that might have influenced the interpretation of the results.

Present the results in the context of the study by describing the extent to which they address the study problem and purpose and contribute to the existing literature and framework described in Chapter 2.

Describe the extent to which the results are consistent with existing research and theory and provide potential explanations for unexpected or divergent results.

Identify the most significant implications and consequences of the dissertation (whether positive and/or negative) to society/desired societal outcomes and distinguish probable from improbable implications.

### RQ1

What is the effectiveness of autonomous assistants for episodic falling syndrome in elderly and special needs care organizations?

### RQ2

What is the efficiency of autonomous assistance for episodic falling syndrome in elderly and special needs care organizations?

## Recommendations for Practice

Begin writing here…

Checklist:

Discuss recommendations for how the findings of the study can be applied to practice and/or theory. Support all the recommendations with at least one finding from the study and frame them in the literature from Chapter 2.

Do not overstate the applicability of the findings.

## Recommendations for Future Research

Begin writing here…

Checklist:

Based on the framework, findings, and implications, explain what future researchers might do to learn from and build upon this study. Justify these explanations.

Discuss how future researchers can improve upon this study, given its limitations.

Explain what the next logical step is in this line of research.

## Conclusions

Begin writing here…

Checklist:

Provide a strong, concise conclusion to include a summary of the study, the problem addressed, and the importance of the study.

Present the “take-home message” of the entire study.

Emphasize what the results of the study mean concerning previous research and either theory (PhD studies) or practice (applied studies).

# Appendix

## Appendix 1: Categories

The kinetic-700 training set videos that were processed successfully specify the following labels. This accounts

|  |  |
| --- | --- |
| Category | Total |
| abseiling | 679 |
| acting in play | 628 |
| adjusting glasses | 464 |
| air drumming | 583 |
| alligator wrestling | 531 |
| answering questions | 443 |
| applauding | 562 |
| applying cream | 475 |
| archaeological excavation | 561 |
| archery | 791 |
| arguing | 518 |
| arm wrestling | 737 |
| arranging flowers | 724 |
| arresting | 422 |
| assembling bicycle | 505 |
| assembling computer | 675 |
| attending conference | 491 |
| auctioning | 647 |
| baby waking up | 480 |
| backflip (human) | 723 |
| baking cookies | 659 |
| bandaging | 788 |
| barbequing | 692 |
| bartending | 611 |
| base jumping | 506 |
| bathing dog | 649 |
| battle rope training | 824 |
| beatboxing | 838 |
| bee keeping | 787 |
| being excited | 584 |
| being in zero gravity | 478 |
| belly dancing | 344 |
| bench pressing | 809 |
| bending back | 505 |
| bending metal | 631 |
| biking through snow | 708 |
| blasting sand | 765 |
| blending fruit | 499 |
| blowdrying hair | 688 |
| blowing bubble gum | 677 |
| blowing glass | 651 |
| blowing leaves | 651 |
| blowing nose | 651 |
| blowing out candles | 881 |
| bobsledding | 570 |
| bodysurfing | 771 |
| bookbinding | 764 |
| bottling | 575 |
| bouncing ball (not juggling) | 478 |
| bouncing on bouncy castle | 694 |
| bouncing on trampoline | 778 |
| bowling | 789 |
| braiding hair | 725 |
| breading or breadcrumbing | 554 |
| breakdancing | 708 |
| breaking boards | 765 |
| breaking glass | 511 |
| breathing fire | 572 |
| brush painting | 743 |
| brushing floor | 567 |
| brushing hair | 784 |
| brushing teeth | 855 |
| building cabinet | 596 |
| building lego | 531 |
| building sandcastle | 686 |
| building shed | 451 |
| bulldozing | 559 |
| bungee jumping | 635 |
| burping | 628 |
| busking | 837 |
| calculating | 558 |
| calligraphy | 598 |
| canoeing or kayaking | 691 |
| capoeira | 802 |
| capsizing | 498 |
| card stacking | 481 |
| card throwing | 454 |
| carrying baby | 542 |
| carrying weight | 488 |
| cartwheeling | 851 |
| carving ice | 637 |
| carving marble | 462 |
| carving pumpkin | 693 |
| carving wood with a knife | 469 |
| casting fishing line | 556 |
| catching fish | 695 |
| catching or throwing baseball | 809 |
| catching or throwing frisbee | 683 |
| catching or throwing softball | 670 |
| celebrating | 794 |
| changing gear in car | 503 |
| changing oil | 764 |
| changing wheel (not on bike) | 825 |
| chasing | 484 |
| checking tires | 723 |
| checking watch | 472 |
| cheerleading | 755 |
| chewing gum | 552 |
| chiseling stone | 461 |
| chiseling wood | 451 |
| chopping meat | 575 |
| chopping wood | 836 |
| clam digging | 537 |
| clapping | 793 |
| clay pottery making | 780 |
| clean and jerk | 843 |
| cleaning gutters | 563 |
| cleaning pool | 569 |
| cleaning shoes | 713 |
| cleaning toilet | 619 |
| cleaning windows | 759 |
| climbing a rope | 843 |
| climbing ladder | 678 |
| climbing tree | 758 |
| closing door | 461 |
| coloring in | 396 |
| combing hair | 473 |
| contact juggling | 493 |
| contorting | 566 |
| cooking chicken | 608 |
| cooking egg | 759 |
| cooking on campfire | 589 |
| cooking sausages (not on barbeque) | 809 |
| cooking scallops | 533 |
| cosplaying | 585 |
| coughing | 444 |
| counting money | 624 |
| country line dancing | 257 |
| cracking back | 470 |
| cracking knuckles | 502 |
| cracking neck | 396 |
| crawling baby | 867 |
| crocheting | 477 |
| crossing eyes | 664 |
| crossing river | 844 |
| crying | 583 |
| cumbia | 558 |
| curling (sport) | 580 |
| curling eyelashes | 494 |
| curling hair | 674 |
| cutting apple | 485 |
| cutting cake | 511 |
| cutting nails | 735 |
| cutting orange | 470 |
| cutting pineapple | 749 |
| cutting watermelon | 681 |
| dancing ballet | 502 |
| dancing charleston | 616 |
| dancing gangnam style | 505 |
| dancing macarena | 498 |
| deadlifting | 797 |
| dealing cards | 476 |
| decorating the christmas tree | 624 |
| decoupage | 528 |
| delivering mail | 484 |
| digging | 563 |
| dining | 620 |
| directing traffic | 515 |
| disc golfing | 583 |
| diving cliff | 628 |
| docking boat | 512 |
| dodgeball | 720 |
| doing aerobics | 642 |
| doing jigsaw puzzle | 484 |
| doing laundry | 464 |
| doing nails | 749 |
| doing sudoku | 501 |
| drawing | 578 |
| dribbling basketball | 828 |
| drinking shots | 649 |
| driving car | 696 |
| driving tractor | 803 |
| drooling | 569 |
| drop kicking | 715 |
| drumming fingers | 584 |
| dumpster diving | 536 |
| dunking basketball | 808 |
| dyeing eyebrows | 441 |
| dyeing hair | 507 |
| eating burger | 742 |
| eating cake | 853 |
| eating carrots | 512 |
| eating chips | 708 |
| eating doughnuts | 670 |
| eating hotdog | 650 |
| eating ice cream | 850 |
| eating nachos | 498 |
| eating spaghetti | 859 |
| eating watermelon | 631 |
| egg hunting | 738 |
| embroidering | 745 |
| entering church | 512 |
| exercising arm | 602 |
| exercising with an exercise ball | 807 |
| extinguishing fire | 550 |
| faceplanting | 769 |
| falling off bike | 647 |
| falling off chair | 684 |
| feeding birds | 838 |
| feeding fish | 836 |
| feeding goats | 747 |
| fencing (sport) | 655 |
| fidgeting | 539 |
| filling cake | 517 |
| filling eyebrows | 488 |
| finger snapping | 799 |
| fixing bicycle | 435 |
| fixing hair | 491 |
| flint knapping | 491 |
| flipping bottle | 393 |
| flipping pancake | 830 |
| fly tying | 750 |
| flying kite | 704 |
| folding clothes | 705 |
| folding napkins | 749 |
| folding paper | 791 |
| front raises | 825 |
| frying vegetables | 720 |
| gargling | 493 |
| geocaching | 515 |
| getting a haircut | 601 |
| getting a piercing | 756 |
| getting a tattoo | 775 |
| giving or receiving award | 715 |
| gold panning | 610 |
| golf chipping | 600 |
| golf driving | 845 |
| golf putting | 548 |
| gospel singing in church | 565 |
| grinding meat | 465 |
| grooming cat | 484 |
| grooming dog | 747 |
| grooming horse | 701 |
| gymnastics tumbling | 699 |
| hammer throw | 849 |
| hand washing clothes | 548 |
| head stand | 734 |
| headbanging | 732 |
| headbutting | 695 |
| helmet diving | 652 |
| herding cattle | 502 |
| high fiving | 584 |
| high jump | 825 |
| high kick | 813 |
| historical reenactment | 743 |
| hitting baseball | 693 |
| hockey stop | 551 |
| holding snake | 590 |
| home roasting coffee | 525 |
| hopscotch | 729 |
| hoverboarding | 577 |
| huddling | 630 |
| hugging (not baby) | 803 |
| hugging baby | 551 |
| hula hooping | 667 |
| hurdling | 704 |
| hurling (sport) | 733 |
| ice climbing | 732 |
| ice fishing | 738 |
| ice skating | 610 |
| ice swimming | 480 |
| inflating balloons | 785 |
| installing carpet | 594 |
| ironing | 744 |
| ironing hair | 523 |
| javelin throw | 688 |
| jaywalking | 531 |
| jetskiing | 515 |
| jogging | 585 |
| juggling balls | 680 |
| juggling fire | 605 |
| juggling soccer ball | 771 |
| jumping bicycle | 513 |
| jumping into pool | 711 |
| jumping jacks | 662 |
| jumping sofa | 647 |
| jumpstyle dancing | 602 |
| karaoke | 583 |
| kicking field goal | 771 |
| kicking soccer ball | 798 |
| kissing | 373 |
| kitesurfing | 676 |
| knitting | 831 |
| krumping | 800 |
| land sailing | 661 |
| laughing | 781 |
| lawn mower racing | 563 |
| laying bricks | 637 |
| laying concrete | 717 |
| laying decking | 502 |
| laying stone | 489 |
| laying tiles | 564 |
| leatherworking | 609 |
| letting go of balloon | 517 |
| licking | 506 |
| lifting hat | 504 |
| lighting candle | 501 |
| lighting fire | 381 |
| listening with headphones | 416 |
| lock picking | 835 |
| long jump | 840 |
| longboarding | 702 |
| looking at phone | 447 |
| looking in mirror | 535 |
| luge | 519 |
| lunge | 827 |
| making a cake | 457 |
| making a sandwich | 603 |
| making balloon shapes | 784 |
| making bubbles | 633 |
| making cheese | 531 |
| making horseshoes | 499 |
| making jewelry | 736 |
| making latte art | 575 |
| making paper aeroplanes | 498 |
| making pizza | 796 |
| making slime | 490 |
| making snowman | 556 |
| making sushi | 687 |
| making tea | 530 |
| making the bed | 762 |
| marching | 815 |
| marriage proposal | 565 |
| massaging back | 537 |
| massaging feet | 459 |
| massaging legs | 481 |
| massaging neck | 439 |
| massaging person's head | 498 |
| metal detecting | 457 |
| milking cow | 844 |
| milking goat | 520 |
| mixing colours | 492 |
| moon walking | 585 |
| mopping floor | 737 |
| mosh pit dancing | 537 |
| motorcycling | 670 |
| mountain climber (exercise) | 816 |
| moving baby | 493 |
| moving child | 544 |
| moving furniture | 611 |
| mowing lawn | 841 |
| mushroom foraging | 498 |
| needle felting | 532 |
| news anchoring | 613 |
| opening bottle (not wine) | 824 |
| opening coconuts | 641 |
| opening door | 563 |
| opening present | 856 |
| opening refrigerator | 568 |
| opening wine bottle | 589 |
| packing | 627 |
| paragliding | 726 |
| parasailing | 798 |
| parkour | 451 |
| passing American football (in game) | 557 |
| passing American football (not in game) | 803 |
| passing soccer ball | 531 |
| peeling apples | 515 |
| peeling banana | 447 |
| peeling potatoes | 491 |
| person collecting garbage | 675 |
| petting animal (not cat) | 714 |
| petting cat | 540 |
| petting horse | 485 |
| photobombing | 492 |
| photocopying | 561 |
| picking apples | 501 |
| picking blueberries | 511 |
| pillow fight | 829 |
| pinching | 484 |
| pirouetting | 692 |
| planing wood | 604 |
| planting trees | 686 |
| plastering | 830 |
| playing accordion | 867 |
| playing american football | 506 |
| playing badminton | 818 |
| playing bagpipes | 866 |
| playing basketball | 652 |
| playing bass guitar | 394 |
| playing beer pong | 674 |
| playing billiards | 486 |
| playing blackjack | 459 |
| playing cards | 469 |
| playing cello | 670 |
| playing checkers | 503 |
| playing chess | 748 |
| playing clarinet | 653 |
| playing controller | 600 |
| playing cricket | 715 |
| playing cymbals | 735 |
| playing darts | 498 |
| playing didgeridoo | 879 |
| playing dominoes | 496 |
| playing drums | 814 |
| playing field hockey | 498 |
| playing flute | 709 |
| playing gong | 608 |
| playing guitar | 677 |
| playing hand clapping games | 534 |
| playing harmonica | 714 |
| playing harp | 816 |
| playing ice hockey | 792 |
| playing keyboard | 802 |
| playing kickball | 509 |
| playing laser tag | 586 |
| playing lute | 543 |
| playing mahjong | 434 |
| playing maracas | 686 |
| playing marbles | 528 |
| playing monopoly | 624 |
| playing netball | 652 |
| playing nose flute | 485 |
| playing oboe | 535 |
| playing ocarina | 739 |
| playing organ | 860 |
| playing paintball | 711 |
| playing pan pipes | 586 |
| playing piano | 814 |
| playing piccolo | 467 |
| playing pinball | 688 |
| playing ping pong | 700 |
| playing poker | 589 |
| playing polo | 603 |
| playing recorder | 750 |
| playing road hockey | 447 |
| playing rounders | 521 |
| playing rubiks cube | 567 |
| playing saxophone | 793 |
| playing scrabble | 500 |
| playing shuffleboard | 533 |
| playing slot machine | 498 |
| playing squash or racquetball | 824 |
| playing tennis | 777 |
| playing trombone | 756 |
| playing trumpet | 817 |
| playing ukulele | 751 |
| playing violin | 716 |
| playing volleyball | 791 |
| playing with trains | 446 |
| playing xylophone | 838 |
| poaching eggs | 464 |
| poking bellybutton | 255 |
| pole vault | 846 |
| polishing furniture | 506 |
| polishing metal | 627 |
| popping balloons | 542 |
| pouring beer | 608 |
| pouring milk | 454 |
| pouring wine | 512 |
| preparing salad | 804 |
| presenting weather forecast | 859 |
| pretending to be a statue | 610 |
| pull ups | 736 |
| pulling espresso shot | 495 |
| pulling rope (game) | 784 |
| pumping fist | 596 |
| pumping gas | 599 |
| punching bag | 738 |
| punching person (boxing) | 459 |
| push up | 808 |
| pushing car | 724 |
| pushing cart | 830 |
| pushing wheelbarrow | 577 |
| pushing wheelchair | 723 |
| putting in contact lenses | 519 |
| putting on eyeliner | 491 |
| putting on foundation | 606 |
| putting on lipstick | 567 |
| putting on mascara | 565 |
| putting on sari | 384 |
| putting on shoes | 475 |
| putting wallpaper on wall | 496 |
| raising eyebrows | 801 |
| reading book | 844 |
| reading newspaper | 591 |
| recording music | 543 |
| repairing puncture | 542 |
| riding a bike | 766 |
| riding camel | 859 |
| riding elephant | 657 |
| riding mechanical bull | 840 |
| riding mule | 603 |
| riding or walking with horse | 588 |
| riding scooter | 808 |
| riding snow blower | 711 |
| riding unicycle | 782 |
| ripping paper | 734 |
| roasting marshmallows | 596 |
| roasting pig | 553 |
| robot dancing | 610 |
| rock climbing | 742 |
| rock scissors paper | 624 |
| roller skating | 690 |
| rolling eyes | 563 |
| rolling pastry | 506 |
| rope pushdown | 843 |
| running on treadmill | 732 |
| sailing | 736 |
| salsa dancing | 427 |
| saluting | 470 |
| sanding floor | 725 |
| sanding wood | 508 |
| sausage making | 515 |
| sawing wood | 564 |
| scrambling eggs | 686 |
| scrapbooking | 594 |
| scrubbing face | 512 |
| scuba diving | 634 |
| seasoning food | 520 |
| separating eggs | 608 |
| setting table | 560 |
| sewing | 647 |
| shaking hands | 632 |
| shaking head | 815 |
| shaping bread dough | 657 |
| sharpening knives | 800 |
| sharpening pencil | 637 |
| shaving head | 609 |
| shaving legs | 500 |
| shearing sheep | 833 |
| shining flashlight | 590 |
| shining shoes | 762 |
| shoot dance | 472 |
| shooting basketball | 765 |
| shooting goal (soccer) | 519 |
| shooting off fireworks | 376 |
| shopping | 501 |
| shot put | 873 |
| shouting | 560 |
| shoveling snow | 850 |
| shredding paper | 437 |
| shucking oysters | 649 |
| shuffling cards | 807 |
| shuffling feet | 777 |
| side kick | 836 |
| sieving | 512 |
| sign language interpreting | 477 |
| silent disco | 638 |
| singing | 580 |
| sipping cup | 723 |
| situp | 829 |
| skateboarding | 445 |
| ski ballet | 538 |
| ski jumping | 497 |
| skiing crosscountry | 658 |
| skiing mono | 479 |
| skiing slalom | 756 |
| skipping rope | 671 |
| skipping stone | 624 |
| skydiving | 625 |
| slacklining | 737 |
| slapping | 779 |
| sled dog racing | 735 |
| sleeping | 653 |
| slicing onion | 529 |
| smashing | 606 |
| smelling feet | 558 |
| smoking | 250 |
| smoking hookah | 597 |
| smoking pipe | 541 |
| snatch weight lifting | 829 |
| sneezing | 674 |
| snorkeling | 576 |
| snowboarding | 656 |
| snowkiting | 498 |
| snowmobiling | 763 |
| somersaulting | 845 |
| spelunking | 786 |
| spinning plates | 510 |
| spinning poi | 548 |
| splashing water | 567 |
| spray painting | 690 |
| spraying | 544 |
| springboard diving | 482 |
| square dancing | 574 |
| squat | 752 |
| squeezing orange | 509 |
| stacking cups | 505 |
| stacking dice | 647 |
| standing on hands | 602 |
| staring | 574 |
| steer roping | 647 |
| steering car | 542 |
| sticking tongue out | 762 |
| stomping grapes | 586 |
| stretching arm | 818 |
| stretching leg | 789 |
| sucking lolly | 415 |
| surfing crowd | 847 |
| surfing water | 775 |
| surveying | 472 |
| sweeping floor | 718 |
| swimming backstroke | 597 |
| swimming breast stroke | 742 |
| swimming butterfly stroke | 543 |
| swimming front crawl | 481 |
| swimming with dolphins | 505 |
| swimming with sharks | 573 |
| swing dancing | 622 |
| swinging baseball bat | 606 |
| swinging on something | 831 |
| sword fighting | 813 |
| sword swallowing | 419 |
| tackling | 617 |
| tagging graffiti | 578 |
| tai chi | 614 |
| taking photo | 458 |
| talking on cell phone | 641 |
| tango dancing | 487 |
| tap dancing | 738 |
| tapping guitar | 850 |
| tapping pen | 702 |
| tasting beer | 609 |
| tasting food | 732 |
| tasting wine | 512 |
| testifying | 478 |
| texting | 445 |
| threading needle | 497 |
| throwing axe | 716 |
| throwing ball (not baseball or American football) | 812 |
| throwing discus | 839 |
| throwing knife | 550 |
| throwing snowballs | 703 |
| throwing tantrum | 567 |
| throwing water balloon | 576 |
| tickling | 494 |
| tie dying | 452 |
| tightrope walking | 721 |
| tiptoeing | 479 |
| tobogganing | 812 |
| tossing coin | 499 |
| tossing salad | 493 |
| training dog | 644 |
| trapezing | 561 |
| treating wood | 507 |
| trimming or shaving beard | 723 |
| trimming shrubs | 508 |
| trimming trees | 688 |
| triple jump | 818 |
| twiddling fingers | 489 |
| tying bow tie | 630 |
| tying knot (not on a tie) | 840 |
| tying necktie | 712 |
| tying shoe laces | 730 |
| unboxing | 623 |
| uncorking champagne | 499 |
| unloading truck | 556 |
| using a microscope | 484 |
| using a paint roller | 559 |
| using a power drill | 503 |
| using a sledge hammer | 680 |
| using a wrench | 527 |
| using atm | 526 |
| using bagging machine | 605 |
| using circular saw | 486 |
| using inhaler | 513 |
| using megaphone | 484 |
| using puppets | 649 |
| using remote controller (not gaming) | 703 |
| using segway | 729 |
| vacuuming car | 499 |
| vacuuming floor | 842 |
| visiting the zoo | 642 |
| wading through mud | 544 |
| wading through water | 530 |
| waiting in line | 655 |
| waking up | 768 |
| walking on stilts | 652 |
| walking the dog | 758 |
| walking through snow | 642 |
| walking with crutches | 538 |
| washing dishes | 691 |
| washing feet | 528 |
| washing hair | 462 |
| washing hands | 808 |
| watching tv | 607 |
| water skiing | 775 |
| water sliding | 836 |
| watering plants | 838 |
| waving hand | 639 |
| waxing armpits | 517 |
| waxing back | 485 |
| waxing chest | 672 |
| waxing eyebrows | 524 |
| waxing legs | 718 |
| weaving basket | 754 |
| weaving fabric | 647 |
| welding | 827 |
| whistling | 620 |
| windsurfing | 442 |
| winking | 633 |
| wood burning (art) | 592 |
| wrapping present | 737 |
| wrestling | 709 |
| writing | 610 |
| yarn spinning | 658 |
| yawning | 607 |
| yoga | 471 |
| zumba | 404 |

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