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Ontology-Driven Monitoring System for Ambient Assisted Living

Work presented in partial fulfillment of the requirements for the degree of Bachelor in Computer Science

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“Ce qu’on voit et ce qu’on ne voit pas”

— FRÉDÉRIC BASTIAT

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ABSTRACT

As the global population ages, the demand for effective home healthcare solutions becomes increasingly essential. Over a decade ago, Ambient Assisted Living (AAL) emerged as a promising solution, especially when combined with the potential of the Internet of Things (IoT) to revolutionize healthcare delivery. However, the integration of diverse smart home devices with healthcare systems poses challenges in interoperability and real-time, context-aware responses. Addressing these challenges, this study introduces an ontology for AAL that seamlessly merges IoT and Smart Home ontologies with the established healthcare ontology, SNOMED CT. This ontology-centric approach facilitates semantic interoperability and also facilitates knowledge sharing, paving the way for more personalized healthcare delivery. At the core of our research lies the development of an AAL monitoring system grounded in this ontology. By incorporating SWRL rules, the system is equipped to provide context-sensitive automated alerts and responses, taking into account patient-specific details, household features, and instantaneous sensor data. Empirical testing conducted in the Halmstad Intelligent Home (HINT) environment underscores the system's viability for practical deployment. The overarching objective is to elevate healthcare provision in AAL spaces, prioritizing patient safety and proactive health oversight. Preliminary results indicate that our integrative, ontology-driven strategy holds significant potential to enhance healthcare services in AAL environments, marking an essential step towards achieving personalized, patient-centric care.

Keywords: Ambient Assisted Living. Internet of Things. Smart Home. Healthcare. Ontology. Context Awareness.

Sistema de Monitoramento Orientado por Ontologia para Vida Assistida Ambientalmente

RESUMO

À medida que a população global envelhece, a demanda por soluções eficazes de assistência médica domiciliar torna-se cada vez mais essencial. O Ambient Assisted Living (AAL), ou Vida Assistida Ambientalmente, surge como uma solução promissora, especialmente quando combinado com o potencial da Internet das Coisas (IoT) para revolucionar a prestação de cuidados de saúde. No entanto, a integração de diversos dispositivos inteligentes em residências com sistemas de saúde apresenta desafios em interoperabilidade e respostas em tempo real, sensíveis ao contexto. Abordando esses desafios, este estudo introduz uma ontologia para AAL que integra conceitos de IoT e Smart Home com a ontologia de saúde estabelecida, SNOMED CT. Esta abordagem facilita a interoperabilidade semântica e também promove o compartilhamento de conhecimento, pavimentando o caminho para uma prestação de cuidados de saúde mais personalizada. No cerne de nossa pesquisa está o desenvolvimento de um sistema de monitoramento AAL fundamentado nesta ontologia. Ao incorporar regras SWRL, o sistema está equipado para fornecer alertas e respostas automatizadas sensíveis ao contexto, levando em consideração detalhes específicos do paciente, características do domicílio e dados instantâneos de sensores. Os testes empíricos realizados no ambiente Halmstad Intelligent Home (HINT) destacam a viabilidade do sistema para implantação prática. O objetivo principal é elevar a prestação de cuidados de saúde em espaços AAL, priorizando a segurança do paciente e a supervisão proativa da saúde. Os resultados preliminares indicam que nossa estratégia integrativa e orientada por ontologia possui um potencial significativo para melhorar os serviços de saúde em ambientes AAL, representando um passo essencial em direção a alcançar um atendimento centrado e personalizado ao paciente.

Palavras-chave: Vida Assistida Ambientalmente. Internet das Coisas. Casa Inteligente. Assistência Médica. Ontologia. Consciência de Contexto.

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LIST OF ABBREVIATIONS AND ACRONYMS

AAL	Ambient Assisted Living
AI	Artificial Intelligence
API	Application Program interface
CPU	Central Processing Unit
DogOnt	Domotic Ontology
EHR	Electronic Health Record
HINT	Halmstad Intelligent Home
ICD	International Classification of Diseases
ICT	Information and Communications Technology
IoT	Internet of Things
IIoT	Industrial Internet of Things
IRI	Internationalized Resource Identifier
IT	Information Technology
ITE	School of Information Technology
LOINC	Logical Observation Identifiers Names and Codes
NLP	Natural Language Processing
OWL	Web Ontology Language
RDF	Resource Description Framework
RDFS	Resource Description Framework Schema
REST	Representational state transfer
SAREF	Smart Appliances REFerence
SNOMED CT	Systematized Nomenclature of Medicine Clinical Terms
SOSA	Sensor, Observation, Sample, and Actuator
SPARQL	SPARQL Protocol and RDF Query Language

SSN	Semantic Sensor Network
SWRL	Semantic Web Rule Language
UI	User Interface
W3C	World Wide Web Consortium

CONTENTS

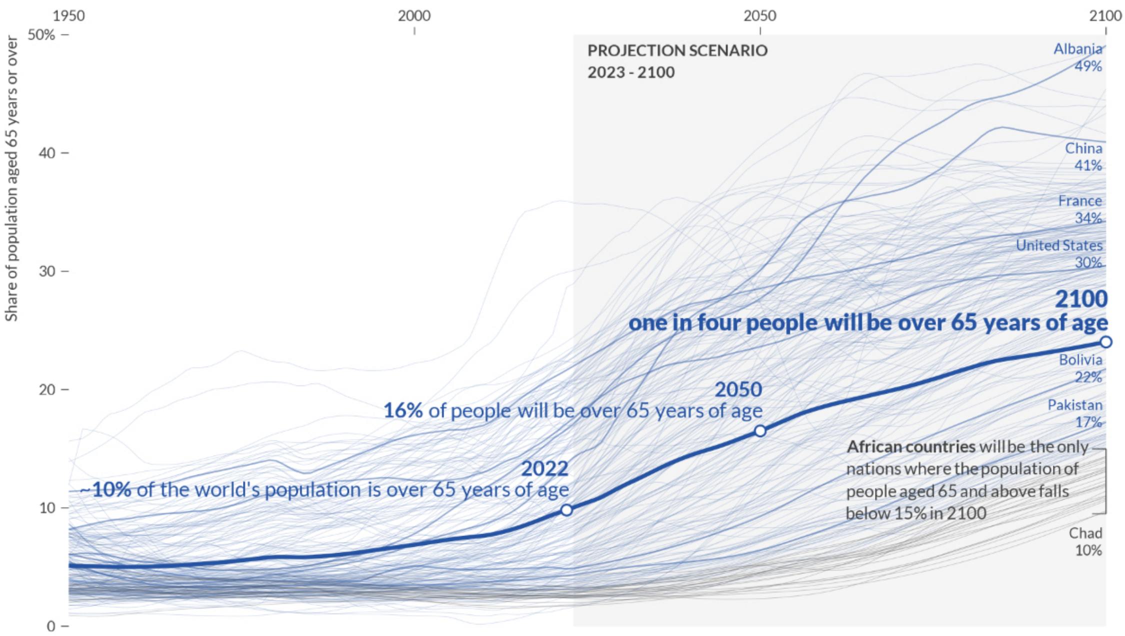
1 INTRODUCTION

This chapter is divided into four sections. The first section outlines the motivations behind this study. In the second section, the study's purpose is presented. The third section enumerates the objectives of the work. Lastly, the fourth section details the structure of the subsequent document.

1.1 Motivation

By 2050, it is estimated that the elderly population aged 65 years or older will increase from 10 percent in 2022 to 16 percent, representing approximately 1.55 billion individuals out of the projected global population of 9.7 billion (United Nations, Department of Economic and Social Affairs, Population Division, 2022). As the global population ages, the demand for healthcare services increases. With longer life expectancy and the incidence of chronic diseases, actions in this field are crucial (PERUZZINI; GERMANI, 2016). Figure 1.1 graphically illustrates the increasing percentage of individuals aged over 65. The showed projections indicate that by 2100, one-fourth of the population will fall into this age group (United Nations, Department of Economic and Social Affairs, Population Division, 2022).

Figure 1.1 – Ageing Population Estimation



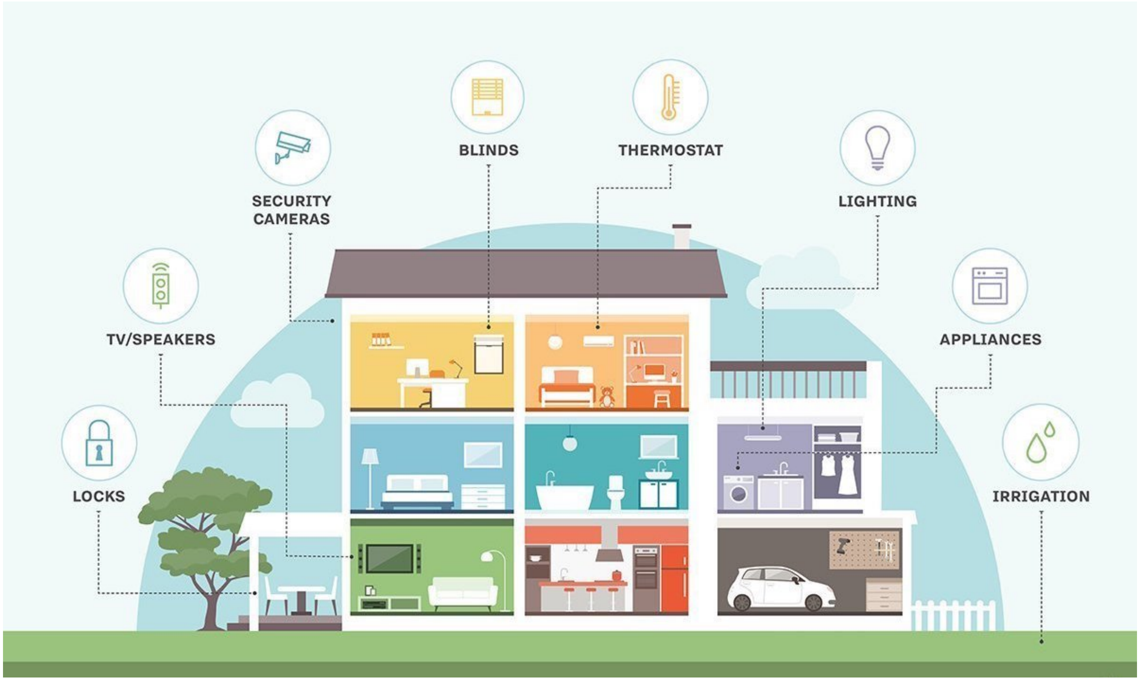
Source: Pablo Alvarez with data from United Nations World Population Prospects (2022)

Considering these factors, home healthcare has emerged as a crucial domain of interest, largely due to clients' preference towards home care as their preferred mode of treatment (JOHNSON et al., 2018). Coupling this with the understanding that the primary challenges lie in preventing institutionalization and preserving patient autonomy, home-based healthcare becomes even more significant (SIEGEL; HOCHGATTERER; DORNER, 2014).

As a result, the requirement for home care services is projected to experience a considerable upsurge. However, the present structure of the healthcare system is inadequately equipped to respond to these growing needs, largely attributed to the scarcity of professionals specializing in the field of geriatric care (KOVNER; MEZEY; HARRINGTON, 2002).

These challenges in healthcare highlight the rising opportunity in using ICT (Information and Communications Technology) to address home healthcare obstacles. Smart home technologies can improve and complement home health care, leading to substantial benefits on the residents' health and quality of life, with cost-effective solutions (SIEGEL; HOCHGATTERER; DORNER, 2014) (EHRENHARD; KIJL; NIEUWENHUIS, 2014). Figure 1.2 showcases examples of devices typically found in a conventional smart home. While these devices often prioritize comfort or security, they hold potential for adaptation to health-related applications.

Figure 1.2 – Smart Home



Source: Adapted from (YASAR, 2018)

The health sector is a complex domain, having an extensive and diverse array of terms and concepts. This presents substantial challenges when attempting to integrate and analyze health-related data and events, particularly those generated by IoT devices within a smart environment, such as a smart home, which also has an escalating complexity and diversity of systems, which in turn introduces significant challenges in their construction, configuration, usage, and maintenance. Adapting these systems to evolving needs and user preferences also poses a considerable challenge (ECKL; MACWILLIAMS, 2009; DEMIRIS et al., 2011). A promising approach to mitigate these challenges involves using ontologies, which can effectively represent the concepts and relationships between various spaces, devices, activities, and services within the home (NING et al., 2019).

Due to the complexity of both domains, the integration of IoT and healthcare requires a coherent framework to ensure accurate data interpretation and interaction. Ontologies provide a structured representation that bridges the terminological differences between these domains. As the proliferation of diverse IoT devices within smart homes continues, a unified ontology-driven approach becomes essential to maintain consistency and adaptability in the integration, promoting a meaningful representation of the data and its interactions with the healthcare field.

1.2 Purpose

Recognizing the missing connection between the healthcare sector and the wealth of data generated by smart environment sensors, this project aims to facilitate personalized, patient-centric health monitoring integrated within the home environment and all its sensors, from wearables to house-related devices. By using the capabilities of modern technology, the goal is to transform homes into dynamic ecosystems that can adapt and respond to the specific health status and needs of their occupants.

The diversity of smart home devices proportionate insights about inhabitants and their environments Beyond their primary functions, these devices harbor potential as valuable health monitoring tools, especially for the elderly and those with chronic diseases. They can have access to enriched, vital data for healthcare practitioners, having a comprehensive picture of an individual's health trajectory.

Achieving this integration provides multiple benefits for both patients and healthcare professionals. For professionals, it promises richer and more accurate data. Those professionals can monitor patients continuously using smart home devices, granting them rapid access to vital health metrics without being physically present. Moreover, integration with the patient's Electronic Health Record (EHR) enables professionals to track health trends. For instance, by integrating a simple device like a scale, they can monitor a patient's weight fluctuations over a year.

For patients, this approach means a greater degree of autonomy and comfort. They can remain in familiar surroundings while being assured of continuous medical oversight. The anticipated outcome is a significant reduction in the frequency of hospitalizations and improved diagnostic precision, timely interventions, and the quality of medical care dispensed. This project aspires to be a convergence point where smart house technology meets healthcare, creating a future where homes are an active participant in the well-being of their inhabitants.

1.3 Objectives

The project aims to propose an ontology-based middleware that allows the interoperability of smart home sensors and actuators for health monitoring. The project outcomes include:

- A new ontology for Ambient Assisted Living environment, connecting the knowledge about smart homes and health domain, based on existing ontologies and designed to fill gaps and provide a connection between both. This ontology will provide a standard vocabulary and structure for representing information related to health monitoring systems in smart environments and facilitate future applications in the field.
- A new ontology-based monitoring system for ambient assisted living that can connect the smart environment sensors data with the healthcare domain, allowing alerts and actions based on the patient information and in the AAL current state provided by the IoT devices.

1.4 Structure

The document's subsequent sections are organized as follows: Chapter 2, titled Fundamentals, explains essential concepts crucial for understanding this study. Chapter 3, Related Work, introduces and briefly discusses key studies that align with the research focus. In Chapter 4, Proposal, the solutions proposed to address the research challenges are detailed. Chapter 5, Experiments, presents a specific use case pertinent to the research. The outcomes from applying the proposed technologies to this use case are explored in Chapter 6, Results, complemented by an in-depth analysis. Subsequently, in Chapter 7, Discussion, a subjective analysis is engaged in, discussing the reasons behind the findings, their implications, and the feasibility of their application as a product. The study culminates in Chapter 8, Conclusion, which encapsulates the research's key contributions and points at potential directions for future works.

2 FUNDAMENTALS

This chapter aims to explain and review the necessary fundamental concepts to understand this study.

2.1 Ambient Assisted Living

In the field of healthcare, the topic of Ambient Assisted Living (AAL) is gaining visibility. The primary purpose mainly concerns delivering supportive care to individuals within their own residences (SIEGEL; HOCHGATTERER; DORNER, 2014). By integrating different IoT devices, AAL aims to oversee, aid, and offer social and cognitive care to individuals starting from the initial stages of an illness, particularly in situations where moderate nursing care are needed (ABDI et al., 2018) (RAVANKAR et al., 2023).

The development of Ambient Assisted Living (AAL) systems has attracted significant attention from the scientific community in recent years. This interest primarily comes from their potential to reduce the financial cost associated with daily life assistance for the elderly, provide continuous monitoring capabilities, ensure the physical and psychological well-being of individuals living alone, and detect subtle behavioral changes, which may signal the onset of diseases in their early stages (G. MARANI R.; T., 2021). Together, these features contribute to the growing interest and investment in AAL technologies, underscoring their importance in modern healthcare and elder care.

2.2 Smart Home

The AAL is based on smart home technologies, which use IoT devices, resulting in a system that monitors the household, learns the routines and preferences of the residents, and takes actions autonomously or with minimal intervention from the resident (COOK; DAS, 2007) (WILSON; HARGREAVES; HAUXWELL-BALDWIN, 2014). Unlike home automation, a smart home is not pre-programmed with fixed rules. The extent of the autonomy determines its "smarts" (BRUSH; HAZAS; ALBRECHT, 2018).

According to (SATPATHY, 2006), “a home which is smart enough to assist the inhabitants to live independently and comfortably with the help of technology is termed a smart home. In a smart home, all the mechanical and digital devices are interconnected to form a network that can communicate with each other and the user to create an interactive space". The concept of a smart home is the integration of IoT devices within residences aiming to improve the health, security, safety and quality of life of the residents (DEMIRIS et al., 2011).

Typically, services to improve physical comfort, security, and energy savings are part of a Smart Home system. Nevertheless, recently, there has been an increased interest in using smart home technologies for healthcare purposes, particularly to monitor and assist older and disabled people living alone. Smart homes have the potential to recognize people's activities and locations and detect problems such as elderly falls. Important application areas of smart homes in the healthcare domain include rehabilitation, assisted living, continuous health, activity monitoring, and response to abnormal situations (DEMIRIS; HENSEL, 2008).

2.3 Internet of Things

Smart homes depend on lower-level technologies that provide sensing and actuation. The term Internet of Things (IoT) describes the interconnection of physical objects and devices that are embedded with sensors, software, and network connectivity, allowing them to collect and exchange data with other devices and systems over the network (MARAIYA; TRIPATHI, 2022) (RAWAT; PANDEY, 2022).

IoT serves as a networking infrastructure, enabling the connection and control of various devices using cutting-edge technologies. The core principle of IoT lies in interconnection, facilitating data collection, resource sharing, analysis, and management across diverse networks. Its primary objective is establishing interconnected networks that transcend boundaries, enabling efficient and integrated operations across heterogeneous environments (LIN et al., 2017).

Internet of Things (IoT) technology has the potential to benefit individuals with disabilities and senior citizens by providing affordable solutions to enhance their independence and quality of life (DOMINGO, 2012). IoT can offer personalized assistance, remote monitoring, and greater control over their environment by seamlessly connecting devices and sensors.

For the effective functioning and meaningful results of the AAL system, there is a necessity for semantic integration among the various devices. This integration facilitates the correlation between data from real-time systems and historical patient records.

Ontologies play an important role in this context, providing a semantic bridge between diverse domains, including smart homes and healthcare concepts.

2.4 Ontologies

Ontologies define the types of entities, attributes of entities, and relationships between entities that can exist within a specific knowledge domain (CHANDRASEKARAN; JOSEPHSON; BENJAMINS, 1999). An ontology serves as a structured vocabulary for expressing and organizing a shared understanding of a given domain, which facilitates communication, knowledge representation, and theory formation about that domain.

Studer states that "An ontology is a formal, explicit specification of a shared conceptualisation" (STUDER; BENJAMINS; FENSEL, 1998). Having a formal definition enables it to be machine-readable and, therefore, allows semantic interoperability and integration of data across heterogeneous systems. This capability is crucial in many applications, such as emergency response, healthcare, and scientific research (FAN; ZLATANOVA, 2011).

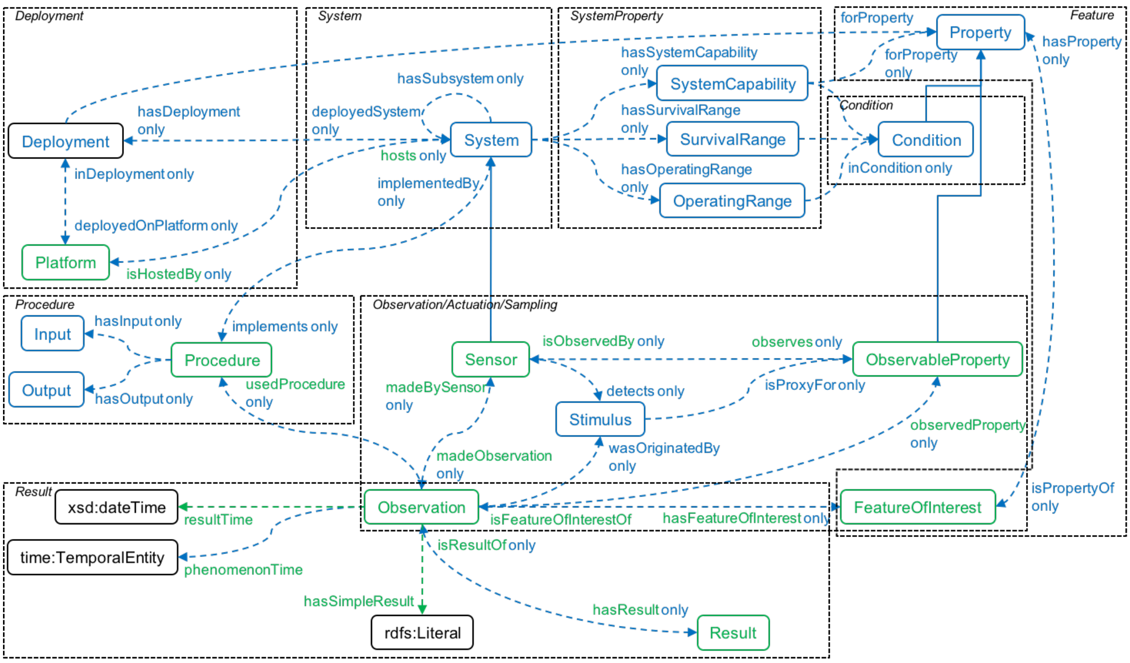
Numerous ontologies exist across various academic disciplines, prominently utilized in systems including search engines, smart cities, natural language processing (NLP), pharmacy, and beyond. The technology sector, as well as the healthcare domain, extensively employ these ontologies. Noteworthy examples in the IT, IoT, and smart home arenas include the SSN (Semantic Sensor Network), SAREF (Smart Appliances REFerence), IoT-Lite, and DogOnt (Domotic Ontology). Similarly, in the healthcare and laboratory sectors, ontologies such as the ICD (International Classification of Diseases), LOINC (Logical Observation Identifiers Names and Codes), and SNOMED CT (Systematized Nomenclature of Medicine Clinical Terms) are prevalent.

2.4.1 SSN and SOSA

The Semantic Sensor Network Ontology (SSN) and Sensor, Observation, Sample, and Actuator (SOSA) are both ontologies related to the field of the Internet of Things. They are used to model, represent and structure information related to sensor networks, their observations, and associated processes. Both ontologies are developed and maintained by the World Wide Web Consortium (W3C) (COMPTON et al., 2012; JANOWICZ et al., 2018).

The SSN ontology focuses on the description and modeling of sensors, their measurements, and the processes involved in capturing these measurements. It provides a framework to represent and link various aspects of sensor data, from the physical device to the generated observations (COMPTON et al., 2012). On the other hand, SOSA serves as a lightweight, simpler ontology, emphasizing the core concepts of sensor operations, observations, and actuation (JANOWICZ et al., 2018). While SSN offers a detailed representation suitable for complex applications, SOSA is designed for broader and more general use cases. Together, these ontologies cater to a wide range of IoT applications, ensuring standardized and interoperable data representation across diverse sensor networks and platforms. Figure 2.1 illustrates the interactions among the entities within the SSN ontology, highlighting, for instance, how a sensor records observations, each associated with a specific result and timestamp.

Figure 2.1 – SSN Ontology



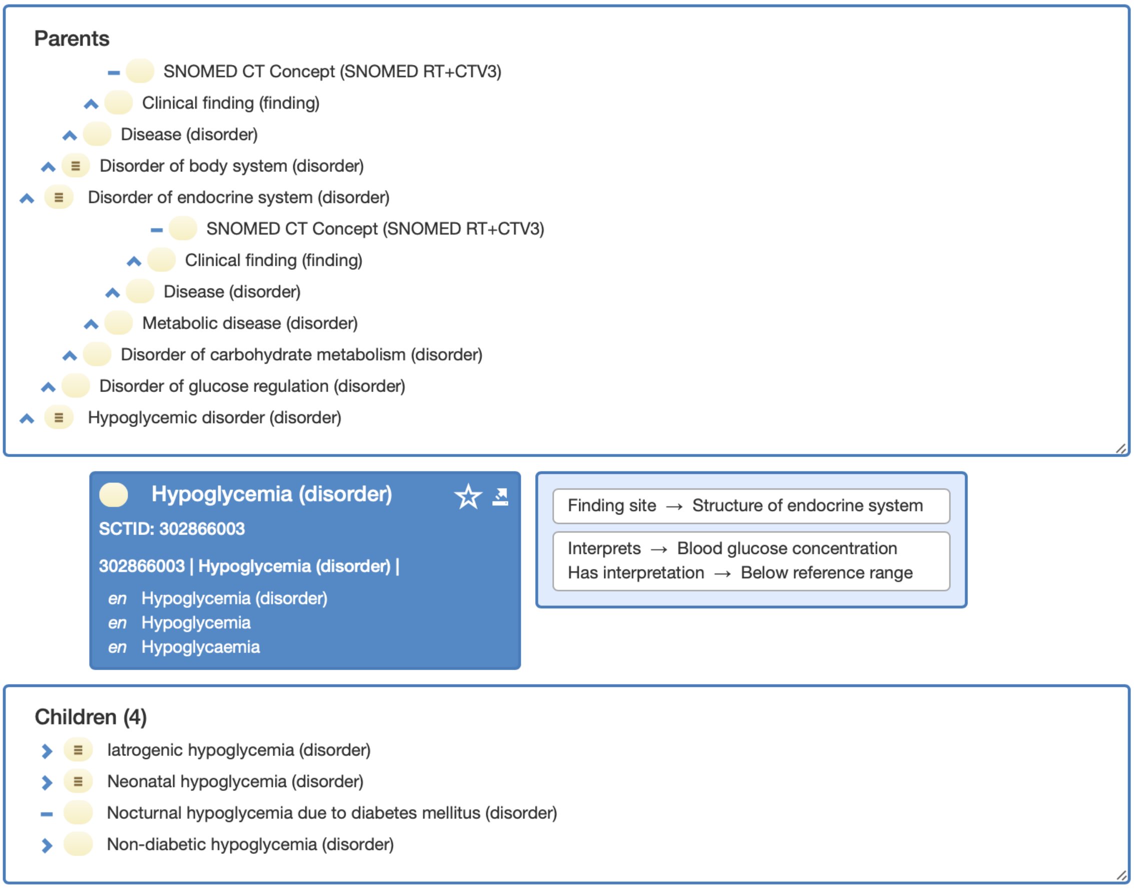
Source: W3C

2.4.2 SNOMED CT

SNOMED CT is a complete clinical terminology that provides a standardized way of representing clinical phrases and medical concepts and their relationships. SNOMED CT is designed to be used in electronic health records (EHRs) and other clinical information systems and to facilitate interoperability and communication across different healthcare systems, such as the electronic exchange of clinical health information. In short, SNOMED CT is a broad clinical terminology used for representing and encoding healthcare information (INTERNATIONAL, 2023a; COMMISSION, 2013). Figure 2.2 illustrates the representation of concepts such as *Hypoglycemia*. It highlights the associated code (referred to as SCTID), alternative names for the disorder, and related information, like the interpretation of hypoglycemia as a blood glucose concentration below the reference range.

SNOMED CT functions as an ontology because it provides a structured and formalized representation of concepts and relationships within the specific domain of clinical medicine. Moreover, as an ontology, SNOMED hierarchically organizes medical concepts into a tree-like structure, with each concept represented by a unique identifier. SNOMED CT is used to support clinical decision-making, research, and quality improvement in healthcare (INTERNATIONAL, 2023a; COMMISSION, 2013).

Figure 2.2 – SNOMED CT Hypoglycemia disorder



Source: The author, from (INTERNATIONAL, 2023b)

2.5 Ontology Mapping

Due to variations in how different domains are expressed and organized within distinct ontologies, using ontology mappings becomes necessary to establish connections between entities, concepts, attributes, and relationships across these ontologies. This process entails identifying similarities or overlaps between the ontologies and creating mappings that link corresponding or related elements together.

Ontology mapping provides a semantic correspondence between different ontologies, serving various purposes such as integration and evolution, data integration, web service composition, search, and query answering (RAMAR; GURUNATHAN, 2016). In the context of this research, there is an effort to architect a mapping between health, IoT, and smart home ontologies. This mapping is not merely an academic exercise but also a strategic initiative aimed at providing interconnectivity among these domains, unlocking new potentials in ambient assisted living environments.

2.6 Resource Description Framework

The Resource Description Framework (RDF) is a foundational standard developed by the World Wide Web Consortium (W3C) for representing structured information about resources on the web. In the context of ontologies, RDF serves as the backbone for encoding, exchanging, and interpreting data semantics. RDF uses a triple-based structure consisting of a subject, predicate, and object (CYGANIAK; WOOD; LANTHALER, 2014). This structure allows for representing statements about resources, effectively capturing relationships and attributes. For instance, the triple (Gabriel, hasHobby, Reading) denotes that "Gabriel's hobby is reading", as the structure is illustrated in Figure 2.3.

Figure 2.3 – An RDF triple example representing that "Gabriel's hobby is reading"

Source: The author

RDF uses Internationalized Resource Identifiers (IRIs) to uniquely identify resources, ensuring global uniqueness and unambiguous interpretation. This is crucial for ontologies, where consistent identification of concepts and relationships is essential. RDF can be easily extended with other standards, such as RDF Schema (RDFS) and the Web Ontology Language (OWL) to provide richer semantics and expressivity, allowing the definition of classes, properties, hierarchies, and more complex relationships (GROUP, 2014; CYGANIAK; WOOD; LANTHALER, 2014).

RDF's standardized format ensures the merging and comprehension of data from diverse domains, a feature particularly valuable for integrating data from different fields. RDF allows data from one domain to reference and link to another, weaving a web of interconnected knowledge. When augmented with RDFS or OWL, it facilitates the semantic annotation of data, transforming raw values into data with explicit meanings and relationships, thereby enhancing understanding and integration. Unlike conventional relational databases, RDF does not necessitate a predetermined schema, allowing for effortless adaptation as new knowledge or relationships emerge in a domain without perturbing the existing data.

2.7 SPARQL

To handle data in RDF databases, it is necessary to have a tool that manages the particularities of this model. The SPARQL Protocol and RDF Query Language (SPARQL) is intrinsically tied to RDF as its primary query language. Designed to retrieve and manipulate data stored in RDF format, SPARQL enables users to make complex queries to RDF datasets and to delete, update, and add data to the RDF graph, making it an indispensable tool. Given RDF's role in representing structured information about resources, SPARQL provides the ways to dive deep into this structured data, extracting specific pieces of information and filtering results based on certain conditions. This capability is especially crucial when working with large and diverse RDF datasets, as it ensures that relevant data can be efficiently retrieved and processed (PRUD'HOMMEAUX; SEABORNE, 2008).

In Listing 2.2, the SPARQL query is designed to extract specific details about observations generated by various sensors. Utilizing the Sensor, Observation, Sample, and Actuator (SOSA) ontology, alongside other standard namespaces, the query retrieves three main pieces of information for each observation: the sensor that made the observation (?s), the property being observed (?p), and the result of the observation (?r). This systematic extraction provides a comprehensive overview of the sensors' observations and their respective results.

The capabilities of SPARQL are key in facilitating the engagement of external

Listing 2.1 – SPARQL query getting the sensor, observed property and value of the observations

```
PREFIX sosa: <http://www.w.org/ns/sosa/>
PREFIX rdf: <http://www.w.org/1999/02/22-rdf-syntax-ns#>
PREFIX skos: <http://www.w.org/2004/02/skos/core#>
PREFIX : <http://www.semanticweb.org/matheusdbampi/aal#>

SELECT ?s ?p ?r
WHERE {
   ?s rdf:type sosa:Sensor .
   ?obs sosa:madeBySensor ?s .
   ?obs sosa:observes ?op .
   ?op skos:prefLabel ?p .
   ?obs sosa:hasSimpleResult ?r
}
```

Source: The author

software with RDF databases. However, while it excels in leveraging ontologies, SPARQL lacks the ability to deduce or infer information based on existing relationships within the graph.

2.8 Reasoning and Semantic Web Rule Language

Reasoning enables the capability of extracting implicit knowledge from explicit facts and relationships defined within the ontology. In essence, reasoning allows for the inference of new information based on the existing structure and content of an ontology. This is achieved by applying logical rules and principles to the relationships and classes defined within the ontology, thereby deducing new facts that were not directly stated but are logically consistent with the given information. The power of reasoning lies in its ability to enrich the knowledge base, making ontologies dynamic and more informative.

Semantic Web Rule Language, or SWRL, is an expressive rule language that extends the set of OWL (Web Ontology Language) axioms to include Horn-like rules (HORROCKS et al., 2004). In the context of ontologies and SPARQL, SWRL provides a mechanism to define more complex relationships and conditions. By defining rules in SWRL, one can capture complex domain-specific knowledge and use reasoning engines to infer new facts based on these rules. When combined with SPARQL queries, this allows for the retrieval of enriched data that includes both explicitly stated facts and those inferred through the rules.

A rule consists of two primary components: an antecedent (called the body) and a consequent (referred to as the head). Each segment comprises zero or more atoms. When the conditions of the antecedent are met, the consequent atoms are activated (HORROCKS et al., 2004). Listing 2.2 provides an illustrative example, with the arrow (->) demarcating the antecedent on the left from the consequent on the right. Interpreting this rule, it posits: 'Given a patient with specified weight and height, if the quotient of the weight divided by the square of the height exceeds 25, then the patient is categorized as having a high BMI.' The mentioned listing also shows the usage of SWRL Built-ins (swrlb), which allow calculations and comparisons with the variables, giving more flexibility and power to the inference rules.

The integration of reasoning with SWRL rules and SPARQL queries can significantly enhance the semantic connection between domains like smart homes and healthcare. For instance, in a scenario where a smart home system collects data on a resident's daily activities and vital signs, SWRL rules can be used to define conditions under which the resident might be considered at risk (such as prolonged inactivity or abnormal heart rates). A healthcare system, equipped with its own ontology about patient care and medical conditions, can then query this inferred data using SPARQL to provide timely interventions or health advice. This ordered and intelligent interconnection between smart home data and healthcare insights, facilitated by reasoning and semantic technologies, can lead to faster responses and personalized care for residents.

Listing 2.2 – SWRL rule example demonstrating the inference of a patient with high body mass index

```
Patient(?p) ^
hasWeight(?p, ?w) ^
hasHeight(?p, ?h) ^
swrlb:divide(?w, swrlb:multiply(?h, ?h), ?bmi) ^
swrlb:greaterThan(?bmi, 25)
->
HighBMI(?p)
```

Source: The author

3 RELATED WORK

This chapter aims to comprehensively review the literature pertinent to our study. By surveying these works, we seek to understand the progress made in the field of AAL and use it as a foundation for our research. Our aim is to enhance existing solutions to the existing challenges in the area. In subsequent sections, we will introduce each of these works and discuss its contribution and how it differs from our proposed approach.

3.1 Ontological Framework of Context-Aware and Reasoning Middleware for Smart Homes with Health and Social Services

In the study (EVCHINA; DVORYANCHIKOVA; LASTRA, 2012), an ontological framework tailored for smart homes is presented. This framework places an emphasis on context-awareness and introduces a novel two-level reasoning middleware to support health and social services within smart home settings. The two-tiered reasoning approach first deduces the overarching system state and subsequently analyzes and filters the derived information. The results underscore the framework's proficiency in using technology to help individual user needs, underscoring its the reasoning importance on ontology-based systems.

This framework has significantly influenced the development of our Ambient Assisted Living (AAL) System. Although it does not mention any specific ontology used and differs from the focus of the current work, particularly, its reasoning methodology has inspired our SWRL rules design. Similarly to the two-level reasoning proposed in (EVCHINA; DVORYANCHIKOVA; LASTRA, 2012), we have categorized the rules into two types: general rules, which infer implicit contextual information, and medical rules, which are rules focused on the health domain to analyze and filter the data to generate the clinical findings.

3.2 An Ontology-based Context-aware System for Smart Homes: E-care@home

A new system called E-care@home is proposed in (ALIREZAIE et al., 2017) to represent semantically activities recognized in a home environment by the devices and its produced data. A reasoning engine was used for the task of extraction and deduction of activities, like determining if someone is watching TV, or cooking in the kitchen, as demonstrated in Table 3.1. Their ontology called *SmartHomeontology* focuses in aspects like time, location and activities of the home's residents.

Table 3.1 – Activities recognized by E-care@home system

	Step	**Activities Recognized**
1	Occupant 1 turns the TV on and sits on the couch	in living room, sitting, watching TV
2	Occupant 1 gets up and fetch the TV program on the table	in living room, moving, watching TV
3	Occupant 1 sits down and watch TV	in living room, sitting, watching TV
4	Occupant 1 goes to the bathroom	in living room, moving
5	Occupant 1 is in the bathroom	in bathroom, moving
6	Occupant 1 goes to the living room	in living room, moving, watching TV
7	Occupant 1 turns the TV off	in living room, moving
8	Occupant 1 exercises	in living room, exercising, high heart rate
9	Occupant 1 goes to the kitchen	in living room, moving
10	Occupant 1 goes to the kitchen	in kitchen, moving
11	Occupant 1 turns the oven on and starts cooking	in kitchen, moving, cooking
12	Occupant 1 goes to the living room	in kitchen, moving, cooking
13	Occupant 1 goes to the living room	in living room, moving, cooking
14	Occupant 1 sits down and read a book	in living room, sitting, burning
15	Occupant 1 goes to kitchen	in living room, moving, cooking
16	Occupant 1 goes to kitchen	in kitchen, moving, cooking
17	Occupant 1 turns the oven off	in kitchen, moving
18	Occupant 1 sits on a chair and drinks tea (stress event)	in kitchen, eating, critical high heart rate

Source: (ALIREZAIE et al., 2017)

This work is extremely relevant and details important aspects of their contributions, such as explaining the proposed ontology. The work (ALIREZAIE et al., 2017) has been important in shaping the current work, especially in the ontology development phase. Their demonstration of the SSN's application in the device domain influenced our decision to reuse this comprehensive ontology.

3.3 Towards an Observer/Controller and Ontology/Rule-Based Approach for Pervasive Healthcare Systems

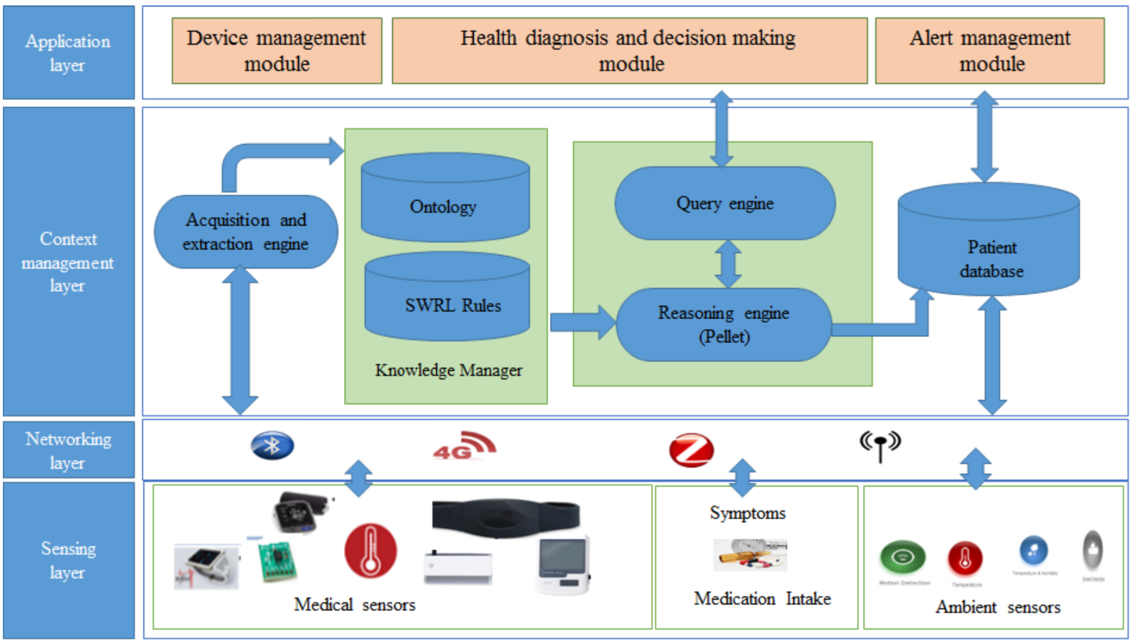
In the same field of research, (HAMEURLAINE et al., 2017) introduces an ontology with a rule-based methodology for systems in healthcare. This system employs SWRL rules to conduct reasoning over the ontology, utilizing sensor data. Their approach does not delineate a specific ontology but significantly emphasises context-awareness. Additionally, it exhibits concern regarding its observer/controller architecture and the deployment on mobile devices, taking into account factors such as battery life and related parameters.

While there are many similarities with the current work, the emphasis of our project shifts from a mobile-centric system to one centered on a smart home environment. The study presented in (HAMEURLAINE et al., 2017) offers significant contributions to system architecture by adopting an observer-controller approach. Furthermore, the manner in which inferences are made from sensor data, with two distinct rule levels, is particularly interesting and inspired our system design. These aspects from (HAMEURLAINE et al., 2017) have been instrumental in shaping and enhancing our work.

3.4 An Ontology-Based Healthcare Monitoring System in the Internet of Things

In another notable study, (TITI; ELHADJ; CHAARI, 2019), a novel ontology is presented, using concepts from both healthcare and the Internet of Things (IoT). The research introduces a rule-based system designed to deduce the immediate health status of a patient. This facilitates the detection of potential health risks, subsequently activating appropriate health services. Figure 3.1 shows the different layers involved in the monitoring system.

Figure 3.1 – System architecture of the IoT monitoring system



Source: (TITI; ELHADJ; CHAARI, 2019)

This ontology is inspired in existing ontologies in both domains of Internet Of Things and healthcare. It is pertinent to highlight that this system, though expansive in its approach, is not designed for smart home contexts and does not consider environmental aspects for full context awareness. This research significantly influenced our project's design and conceptualization, inspiring our SWRL formulation approach.

3.5 OntoDomus: A Semantic Model for Ambient Assisted Living System Based on Smart Homes

In the study (NGANKAM; PIGOT; GIROUX, 2022), the *OntoDomus* ontology is introduced, specifically tailored for Ambient Assisted Living (AAL) environments. This ontology streamlines semantic interactions, ensuring cohesive integration within a smart home. Leveraging SPARQL and OWL, the system is adept at reasoning over contextual data. A notable highlight is its emphasis on activity recognition, exemplified by a use case depicting an elderly individual consuming water during nighttime hours.

The *OntoDomus* ontology, similar to other studies discussed in this section, focuses on discerning activities within a smart home setting. By harnessing the capabilities of the smart environment, it infers the actions and routines of its occupants. This research has been instrumental in shaping our project, particularly in ontology development and the complex relationships between entities, which both projects are in the AAL context.

3.6 DogOnt - Ontology Modeling for Intelligent Domotic Environments

In the study (BONINO; CORNO, 2008), an ontology named textitDogOnt is proposed, made for the complex domain of smart home environments. It differentiates between diverse elements in a smart home, classifying them into controllable entities like sensors and actuators, and uncontrollable entities like beds and doors. DogOnt's precision and adaptability have established a new standard, driving forward progress in the domain of smart home ontologies.

While creating our ontology for Ambient Assisted Living (AAL), we leaned on the foundational concepts of DogOnt. We especially integrated its entities on home architectural parts and in its class hierarchies. However, it is worth noting that the ontology presented in (BONINO; CORNO, 2008) primarily focuses on general smart home functionalities, overlooking specific health-related aspects. Nevertheless, DogOnt was pivotal in informing our methodology, laying a solid groundwork for our environment modeling part.

3.7 A Rule-Based Reasoner for Underwater Robots Using OWL and SWRL

In the study (ZHAI et al., 2018), a rule-based reasoner is introduced for the domain of underwater robots. The research delves into using the power of ontologies to analyse underwater robots during missions. Based on the gathered data, inferences are made regarding the robot's position and many other information, such as determining if the vehicle is in what is termed a "least safe position," represented by the entity *VehicleAtLeastSafetyPosition*. These rules are user-defined, utilizing SWRL rules for its representation capabilities.

While the primary focus of this paper is distinct from the Ambient Assisted Living (AAL) field, its contributions have significantly influenced the current project. Despite the domain differences, parallels can be drawn between an underwater robot's situation and a patient in a smart home facing specific health risks. The methodology and reasoning approach presented in the paper offers valuable insights that can be applied to the AAL domain, emphasizing the adaptability and relevance of rule-based reasoning across diverse fields.

3.8 Summary

The mentioned studies are highly relevant and offer significant contributions to the research field addressed in this paper. These works served as foundational references for the conceptualization and execution of our study. Table 3.2 provides a detailed breakdown of the primary aspects reviewed, classifying them as "Yes", "No", or "Partially" depending on their coverage of specific features. To analyse the selected papers we considered main features that are relevant to the context of the project:

- **Smart Home/AAL:** This criterion determines whether the work pertains to the domain of Smart Home or Ambient Assisted Living. It is essential to ascertain this to identify attributes that align with the present study.
- **New Ontology:** Indicates whether the work introduces a new ontology to address challenges, adopts an alternative approach, or leverages existing ontologies.
- **Health Ontologies:** It assesses if the proposed solution incorporates existing health ontologies or taxonomies, such as LOINC, ICD or SNOMED CT.
- **Patient EHR:** Evaluates whether the solution utilizes information from the pa-

tient's electronic health records (EHR), such as medication intake or prior medical conditions, which are pivotal for monitoring the resident's health status.

Table 3.2 – Comparison on related work

	Work	Smart Home/AAL	New Ontology	Health Ontologies	Patient EHR
Related Works	EVCHINA; DVORYANCHIKOVA; LASTRA 2012	Yes	No	No	No
	ALIREZAIE et al. 2017	Yes	Yes	No	No
	HAMEURLAINE et al. 2017	Yes	Yes	No	No
	TITI; ELHADJ; CHAARI 2019	No	Yes	Partially	Partially
	NGANKAM; PIGOT; GIROUX 2022	Yes	Yes	No	No
	BONINO; CORNO 2008	Yes	Yes	No	No
	ZHAI et al. 2018	No	Yes	No	No
	This Work	Yes	Yes	Yes	Yes

Source: The author

Upon analyzing the contributions and primary solutions addressing this issue, it becomes evident that no existing ontology comprehensively addresses the ambient assisted living (AAL) problem, in contrast to those in the smart home domain. This observation underscores the need for a new AAL ontology that bridges existing gaps and promotes semantic interoperability for home-based healthcare.

Further examination reveals that current solutions predominantly focus on integrating Internet of Things (IoT) devices without context awareness involving other aspects surrounding the patient and the physical environment. They often overlook broader considerations pertinent to the medical domain, such as incorporating electronic health data to provide a more holistic view of patient care. Additionally, there is an evident lack of mechanisms to facilitate integration with established systems, like the use of medical codes from ICD-10 or SNOMED CT.

4 PROPOSED APPROACH

The proposal is divided into two parts: ontology and the AAL system. First, a new ontology for Ambient Assisted Living is proposed, followed by a monitoring system that takes advantage of the proposed ontology.

4.1 Proposed Ontology

The work proposes an ontology based on four existing ontologies: SSN and SOSA from the IoT domain; DogOnt, designed for smart homes; and SNOMED CT, a health-related terminology and ontology. This section will begin by contextualizing these ontologies and elaborating on their contribution to the proposed ontology.

4.1.1 Representing IoT concepts using SSN and SOSA

Integrating the Semantic Sensor Network (SSN) and the Sensor, Observation, Sample, and Actuator (SOSA) ontologies into the proposed framework provides a robust foundation for representing device-related activities within ambient assisted living environments. The SSN ontology, with its emphasis on systems, offers a holistic view of the arrangement of devices or sub-systems. Within our ontology, the *System* entity signifies both wearable systems associated with patients and more extensive systems embedded within the building environment, highlighting the interconnection of devices and their home context.

SOSA plays an important role in detailing the functionalities and interactions of these devices. At its core, SOSA delineates the roles of Sensors and Actuators. While sensors are tasked with observing specific properties, actuators execute actions. This distinction is further enriched by entities like *Observation* and *Actuation*, which capture the nuanced actions of sensors and actuators. The ontology's inclusion of entities such as *FeatureOfInterest*, *ObservableProperty*, and *Procedure* provides depth, allowing for a comprehensive understanding of the observation process, from the specific area a sensor monitors to the characteristic being observed and the methodology employed.

Incorporating SSN and SOSA ensures that the ontology is grounded in established frameworks and has the granularity required for the AAL system. This integration accurately represents how sensors, actuators, and associated systems operate and interact within the smart home.

4.1.2 Representing SmartHome concepts using DogOnt

Incorporating the *DogOnt* into the proposed framework emphasizes the importance of a good representation of the physical environment within ambient assisted living systems. *DogOnt*, a well-structured ontology designed specifically for smart homes and buildings, provides a comprehensive set of terms that describe the physical and functional aspects of living spaces. In our ontology, entities such as *Room*, *BuildingEnvironment* and *BuildingThing* shows how the architectural and environmental elements of a smart home can be represented, ensuring that the spatial context is mapped and connected with the IoT domain.

Integrating *DogOnt* facilitates a richer understanding of how the physical environment interacts with and influences the health and well-being of residents in smart homes. For instance, the ontology can represent the specific rooms a patient frequents and how these spaces are equipped with various systems and devices. This is essential for creating smart home solutions that can adapt and respond to its inhabitants' spatial and environmental needs. For the AAL ontology proposed in our work, ensuring a harmonious integration of technology and its environment is important.

4.1.3 Representing Healthcare concepts using SNOMED CT

Integrating the SNOMED CT (Systematized Nomenclature of Medicine - Clinical Terms) ontology into the proposed framework is due to the significance of standardized medical terminology within ambient assisted living environments. Recognized globally for its comprehensive, multilingual clinical healthcare terminology, SNOMED CT offers a vast array of clinical concepts. Further, it has multiple defined relationships between entities that provide helpful information to be extracted by the reasoning engine, providing useful insights.

Within our ontology, entities such as *Patient*, *Disease*, and *Clinical finding* highlight the medical information that can be represented, ensuring residents' health status and needs are handled with precision. This utilization of SNOMED CT facilitates understanding smart home residents' health-related aspects. Also, it ensures that the system can respond to the diverse health needs of its inhabitants. By extending this, the framework guarantees health-related data's accuracy and interoperability.

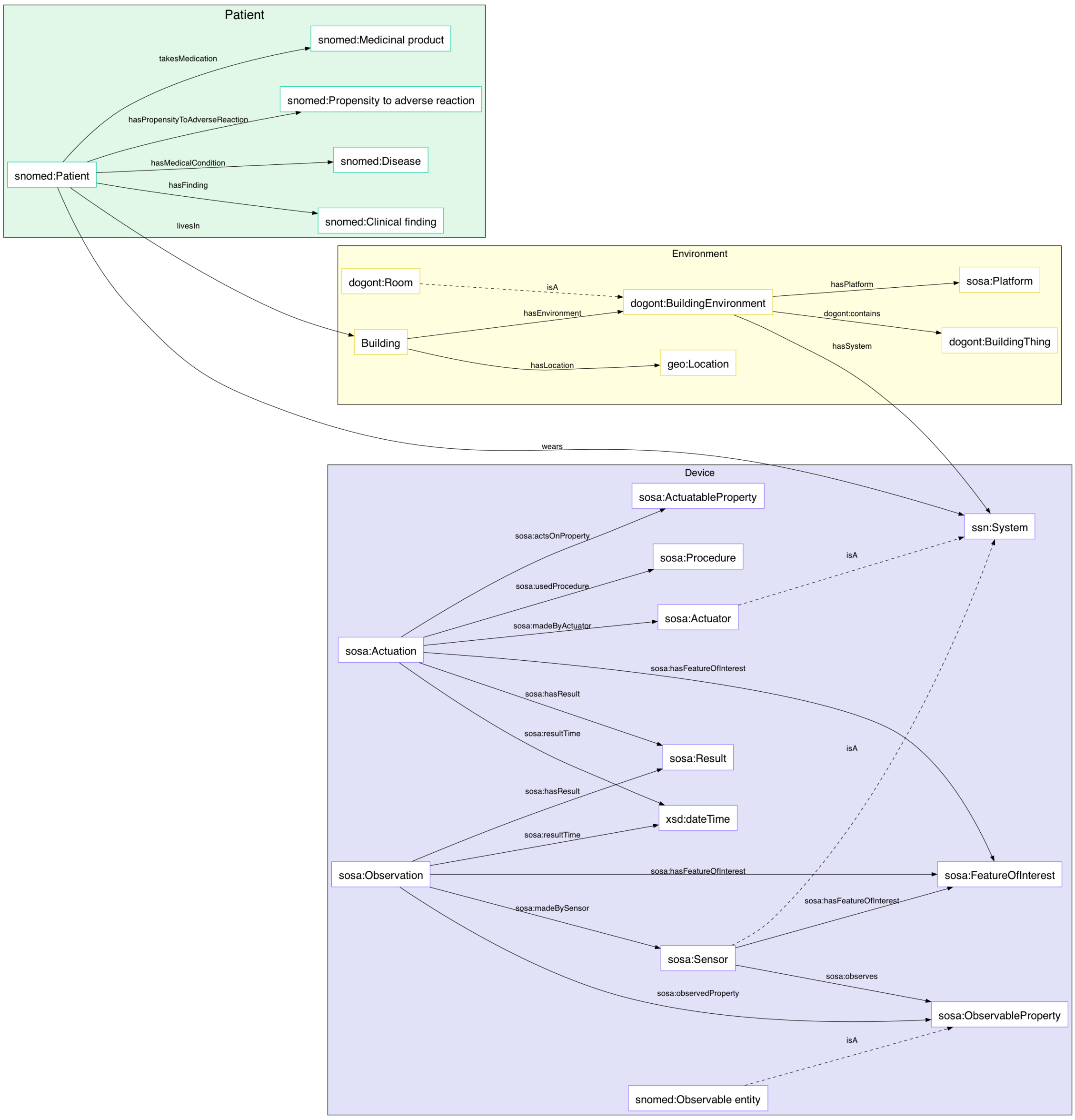
4.1.4 Resulting Ambient Assisted Living Ontology

The presented ontology offers a framework for Ambient Assisted Living environments, emphasizing healthcare integration with smart homes. This ontology is structured around three primary domains: Patient, Environment, and Device. Figure 4.1 visually illustrates some of the main components and relationships of the AAL ontology, such as how a room can have system, that can be an actuator or a sensor that produces observations about a specific observable property.

- **Patient**: This domain captures the health-related aspects of individuals residing in smart homes. It encompasses entities such as the patient himself and their associated health conditions, findings, medications, and potential adverse reactions. The ontology ensures that the health status and needs of the resident are central to the smart home's operations.
- **Environment**: This domain is important in understanding the physical context of the smart home. It includes entities like the building itself, its specific rooms, and the objects in the environment. By defining relationships with objects, such as a bed, located in a specific environment, the ontology connects the health sensors' capabilities in the context of the surrounding environment.
- **Device**: This domain is essential to the smart home's functionality, especially when it comes to the technology parts and its connection with the monitoring system. It encapsulates the various systems, sensors, actuators, and associated operations. These devices can monitor and act upon both the environment and the residents, ensuring that the smart home responds appropriately to its inhabitants' health and comfort needs.

The ontology introduced in this study offers a structured representation of the mentioned divisions inherent to an AAL environment. Developed *ad-hoc*, this ontology strategically employs entities exclusively from established ontological frameworks. Instead of generating new entities, the primary objective centers on articulating innovative relationships among these existing ontologies. These relationships foster a holistic

Figure 4.1 – Proposed AAL Ontology with subdivisions of patient, environment and device



Source: The author

comprehensive perspective, capturing the nuanced interactions between individuals, their ambient environment, and the devices with which they interact. As an illustration, the ontology can elucidate the correlation between a patient's health status and the sensory data derived from their residence, or how environmental adjustments within the home can address to specific health needs of its inhabitants.

In the proposed ontology, specific semantic relationships were introduced to bridge previously disconnected segments, particularly across the device, health, and environment divisions. For instance, the relationship *hasSystem* links *BuildingEnvironment* (an entity from DogOnt) as the domain to *System* (as defined by SSN) as the range of the relationship, elucidating the placement of smart home devices within the physical environment.

Relationships tailored to the healthcare domain were added, interconnecting existing SNOMED CT concepts. Relationships such as *takesMedication*, *hasPropensityToAdverseReaction*, and *hasMedicalCondition* underscore our enhancements to the AAL Ontology, giving a clearer representation of a Patient instance (derived from SNOMED CT) and its relations to key healthcare terminologies of the EHR framework. Notably, these relationships are non-transitive, non-symmetric, and non-reflexive, ensuring a cohesive integration throughout the ontology. Additionally, the introduction of the *hasFinding* relationship is important for the retrieval of new information inferred from the defined medical rules.

In essence, this ontology serves as a blueprint for researchers and developers aiming to create more responsive, health-centric smart home environments. By integrating concepts from health, environmental, and device domains, it provides a multidimensional view of how these areas intersect and interact within the context of AAL. The proposed monitoring system is just one of the multiple applications that can be built upon this ontology as its foundation. The complete AAL ontology file is available in the author's public GitHub repository (BAMPI, 2023).

4.2 Proposed AAL Monitoring System

Utilizing the presented ontology, we designed an Ambient Assisted Living monitoring system to enhance healthcare within domestic environments. By integrating various technologies, the system offers tailored healthcare device management within smart homes. An important enhancement comes from incorporating the patient's electronic health record, which enables health professionals to respond with increased speed and precision.

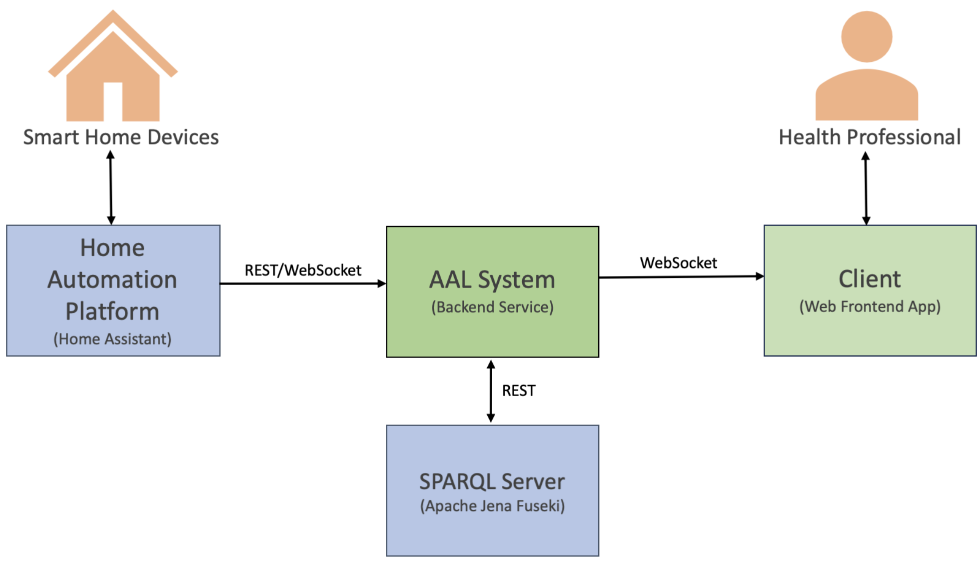
This methodology emphasizes patient comfort and independence, which can lead to fewer hospital visits and timely medical actions. For healthcare professionals, including doctors, nurses, and caregivers, the system provides consistent, in-depth data, improving diagnostic precision. Its integration with EHR facilitates clinical decision-making, enhancing patient care and overall health management. The complete AAL Monitoring System code is available in the author's public GitHub repository (BAMPI, 2023).

4.2.1 System Architecture

The proposed Ambient Assisted Living (AAL) system presents a modular and decoupled design, to ensure flexibility, scalability, and reduced system lock-in. It has been deliberately designed to allow it to operate decentralized, enabling execution across diverse devices and locations. This decentralization and independence are predominantly attributed to incorporating WebSocket and REST connections for inter-module communication. These communication protocols enhance the system's interoperability and adaptability and ensure seamless data exchange. Furthermore, these features enable easy replacements or upgrades of system components, requiring minimal code modifications. This approach consequently ensures that the system remains agile, future-proof, and can quickly adapt to new technologies or user requirements without significant overhauls or downtimes.

In Figure 4.2, the system is presented as being composed of four main modules: the Smart Home Hub (or Home Automation Platform), where Home Assistant was utilized; the SPARQL Server, running the Apache Jena Fuseki; the AAL Client, represented in this case by a web frontend but which could be another application; and the AAL System, serving as the main backend service, connecting all components of the system. The development of the Ambient Assisted Living monitoring system leveraged the capabilities of three primary technologies: Home Assistant, Go, and Apache Jena Fuseki.

Figure 4.2 – System Architecture



Source: The author

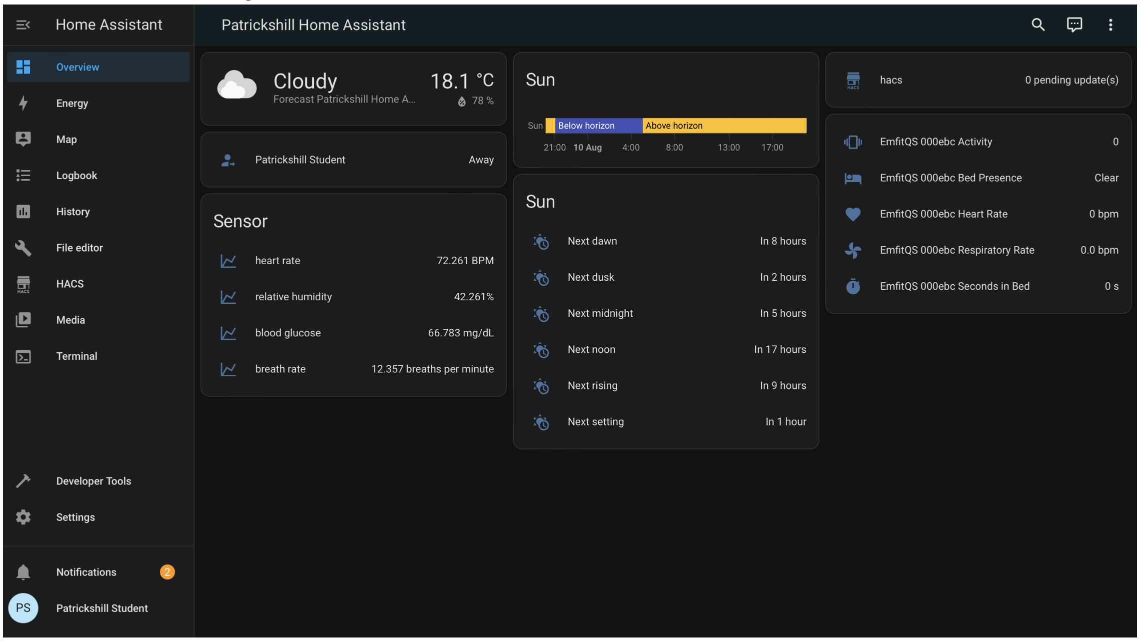
4.2.2 Smart Home Hub

The system we propose is constructed on top of a smart home hub platform, which orchestrates low-level interactions with devices employing a variety of protocols and technologies. For the successful deployment of the Ambient Assisted Living (AAL) System, it presupposes an operational platform interfacing with the diverse devices within the environment. Addressing these protocol disparities was not within the scope of our design, as established platforms, notably Home Assistant (ASSISTANT, 2023), have already proficiently resolved such challenges.

Home Assistant is an open-source smart home hub and home automation platform focused on local control and privacy (ASSISTANT, 2023). The system is written in the programming language Python and is available to community contributions on GitHub. Home Assistant has over 1900 built-in integrations with different protocols and brands, including HomeKit, Amazon Alexa, Google Assistant, Z-Wave and Zigbee (ASSISTANT, 2023). It has an authentication system ensuring privacy and security of the data. The smart home hub also provides an user application for both mobile and web, as demonstrated in image 4.3, facilitating the management and visualisation of devices and system automation. The referenced figure illustrates the primary dashboard from a user's perspective. It facilitates the display of diverse sensor data alongside general information, such the temperature and sunrise/sunset times, specific to the geographic location of the residence.

The Home Assistant provides both a REST API and a WebSocket API, allowing external applications to retrieve information about the devices connected and the current state of each of them (ASSISTANT, 2023). It also allows an external application to subscribe to events, such as state changes of devices, allowing real-time communication. Home assistant was used to ensure the AAL system integration with various smart home devices. This software's flexibility and robustness allowed us to have real-time communication between various sensors and devices, forming a network capable of generating rich data about the home environment, allowing our system to run in a higher level layer.

Figure 4.3 – Home Assistant Web Interface on Overview tab



Source: The author, from Home Assistant

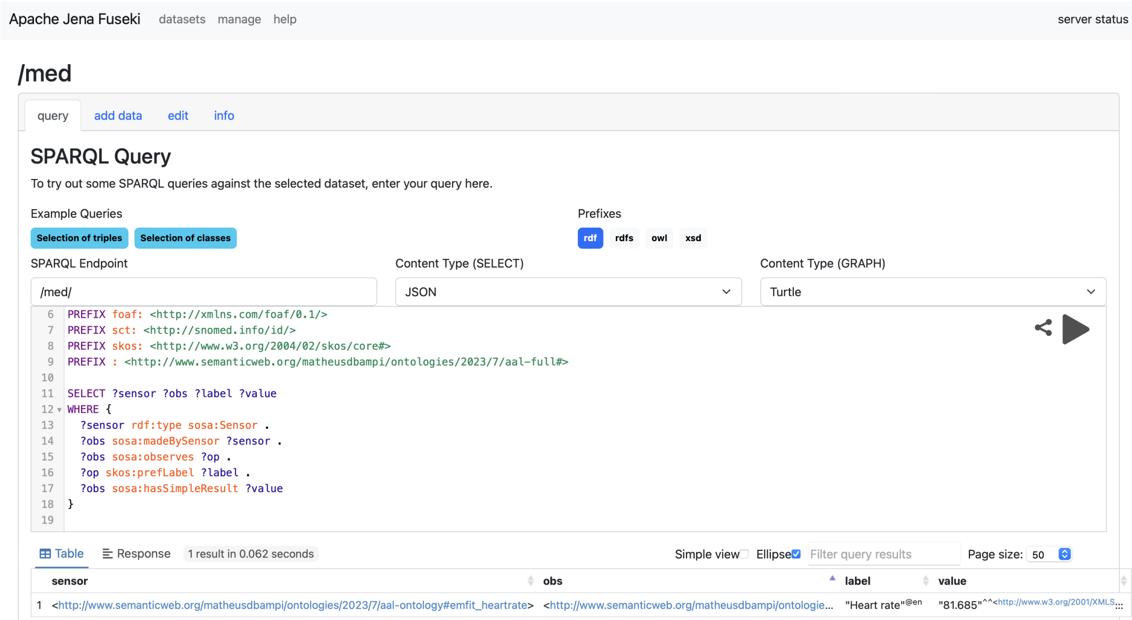
4.2.3 SPARQL Server

In the architecture of our system, the SPARQL server is a central entity, having a graph database and inference capabilities. It is a data storage facility and also actively manages knowledge by housing the instantiated ontology, which covers the domains pertinent to our research, from the physical environment to patient data and sensors. As new observations are integrated into the system, they are inserted into this service. Through the RDF database structure, the SPARQL server interprets these observations using both general and specialized medical rules, facilitating a process that deduces and extrapolates new insights, enriching our comprehension of a patient's health trajectory and potential clinical findings. In our research, Apache Jena Fuseki was utilized in this role.

Apache Jena Fuseki is a SPARQL server that can run as an operating system service, a Java web application, or a standalone server. It provides a robust framework for serving the ontology-based RDF graph features. Fuseki provides the SPARQL Graph Store protocol and SPARQL 1.1 protocols for query and update (FUSEKI, 2023). A web graphical interface is provided, seen in Figure 4.4, providing a friendly way for interacting with the graph.

One feature of the platform is its capability to overlay an inference system on top of the dataset, loading SWRL rules into the server. These rules play an important role in the reasoning process, allowing for the dynamic generation of new RDF triples based on

Figure 4.4 – Apache Jena Fuseki Web Interface on query tab



Source: The author, from Apache Jena Fuseki

predefined conditions and logic. This union of Fuseki's inference capabilities with SWRL rules unlocks powerful possibilities, enabling richer semantic queries and more intelligent data extraction, thus enhancing the depth and breadth of knowledge exploration of the ontology.

Apache Jena Fuseki also serves HTTP API endpoints allowing operations via external applications and facilitating the execution of SPARQL queries in the RDF graph to retrieve, delete, update or delete data.

On our work, the Apache Jena Fuseki server was used running on a Docker container, exposing the HTTP API port, to allow integration with the backend system. The server was configured to load the AAL ontology on startup using a Turtle (*.ttl*) representation of the ontology. It was also set to load the SWRL rules defined on two external files: *general.rules*, containing some inference rules related to the sensors and observations attributes; and *medical.rules*, which consists of rules defined by the health professional to define the clinical finding inferences. As the reasoning engine to perform the defined rules, the Jena Generic Rule Reasoner is being used.

4.2.4 Backend System

The core of our AAL system was developed using Go (or Golang), a statically typed, compiled language known for its simplicity, efficiency, and native support for concurrent programming (GOOGLE, 2023). Golang served as the system's backend, establishing connections with both the Home Assistant platform and the Apache Jena Fuseki SPARQL server. Through the backend system, the AAL various components were able to interact effectively, coordinating the flow of data from the smart home hub to the server, and ultimately serving it via a WebSocket API to enable client connections.

The backend system connects all the parts of the AAL system, receiving information from the smart home hub, storing and manipulating it with the SPARQL server, and serving an API to enable connection from a client - in this case, a web app.

The backend system consists of 4 different modules: smart home connection, SPARQL server connection, AAL manager and API serving. The system connects via REST and WebSocket to Home Assistant with the Home Assistant API, to retrieve information about the home and patient state. Initially, the backend system makes a REST request to receive the current state of all connected sensors in the system. After this step, it subscribes to state change events, via the Home Assistant WebSocket API, running a loop that keeps receiving the events and sending them to the manager. In the AAL Manager, the events are received and processed accordingly.

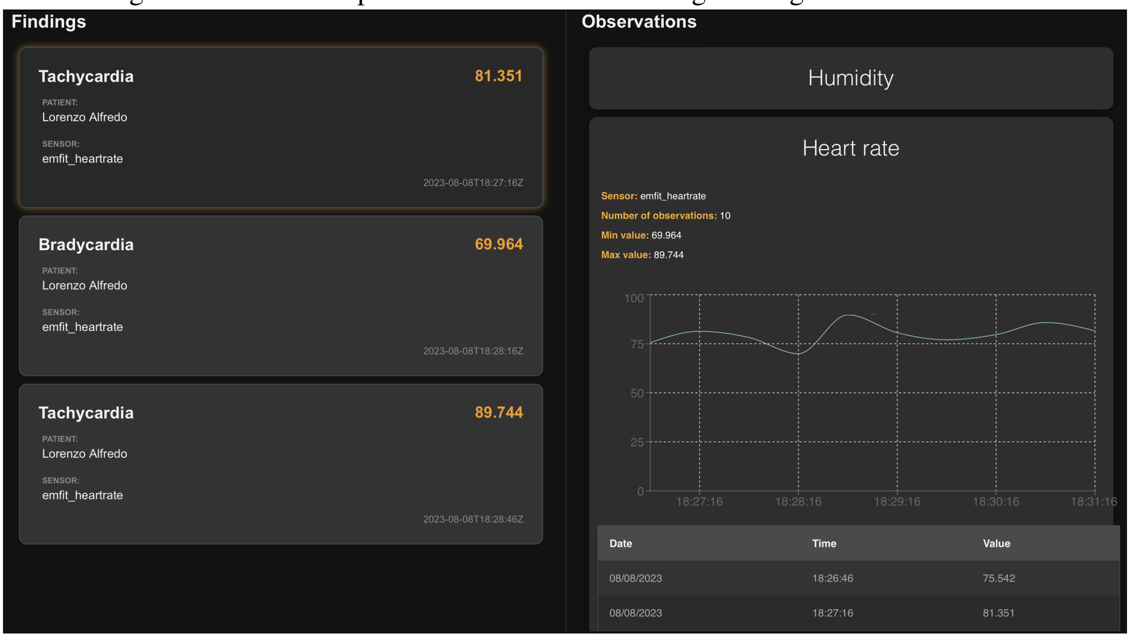
Each event received by the manager module is verified to check if the sensor is registered in the AAL manager. If it is a registered sensor, the system handles the event and adds it to the Apache Jena Fuseki RDF database using a SPARQL Query, saving it as an instance of an Observation (entity imported in AAL ontology from the SOSA ontology). If the event sensor is not recognized, the event is ignored.

After each observation insertion in the RDF database, the AAL Manager runs a SPARQL query to check if any new clinical finding was generated by the reasoning engine. In case of the existence of new findings, the AAL manager sends this information to all connected WebSocket clients.

4.2.5 Frontend

To provide an example application of the core system, it was developed a basic graphical user interface that connects to the backend system via WebSocket and shows both the observations registered by the AAL system and the findings inferred in real-time. The UI (User Interface) was developed using React.js with Typescript, together with the library *recharts*, helping with the plotting of user-friendly charts. It connects via WebSocket to the backend system and provides a read-only web application showing, as demonstrated in Figure 4.5 the last new findings from the system on the left side, and, on the right side, the multiple properties being observed, containing a chart with its values and a table with all registered observations.

Figure 4.5 – Web Graphical User Interface showing Findings and Observations



Source: The author

The frontend, while instrumental, is not the primary emphasis of this study. The AAL System was designed to facilitate diverse data consumption methods, ranging from integration with systems like the one developed, to platforms that dispatch alerts—like emails and text messages to designated recipients. In the case of a patient with asthma, the system can automatically adjust air conditioning temperatures to maintain an environment that reduces the risk of triggering an asthma attack.

5 EXPERIMENTS

This chapter aims to explain in more detail the practical aspects of this work, such as how the experiments were implemented and conducted.

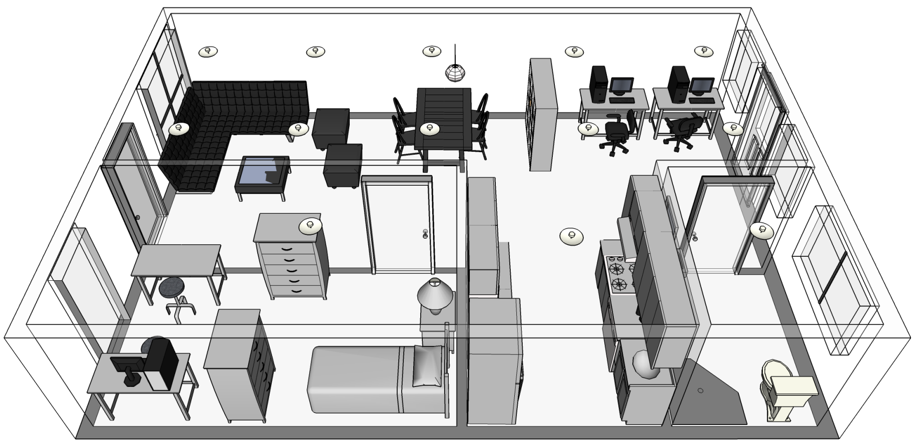
5.1 Halmstad Intelligent Home

The Halmstad Intelligent Home (HINT) is a $50\,\mathrm{m}^2$ apartment equipped with multiple IoT devices, built with the goal of helping researchers and students with experiments and studies related to the area of Smart Home and related subjects. HINT is located in the Halmstad University campus in the city of Halmstad, Halland, Sweden and financed by the School of Information Technology (ITE). Figure 5.1 depicts the floor plan of the Halmstad Intelligent Home, featuring a bedroom, bathroom, kitchen, and a living room.

The apartment has more than 60 sensors and actuators, from magnetic switches to detect the opening and closing of doors and drawers to motor actuators to enable different bed positions. The environment is controlled by the Home Assistant, an open-source home automation platform and smart home hub (COMMUNITY, 2023).

This well-equipped smart environment serves as the primary use case for the project, allowing for a detailed analysis of usability, performance, and results. By utilizing HINT, the effectiveness of the system can be closely examined, and areas for improvement identified, thereby ensuring valuable insights and advancements in the field of Ambient Assisted Living.

Figure 5.1 – Halmstad Intelligent Home floor plan

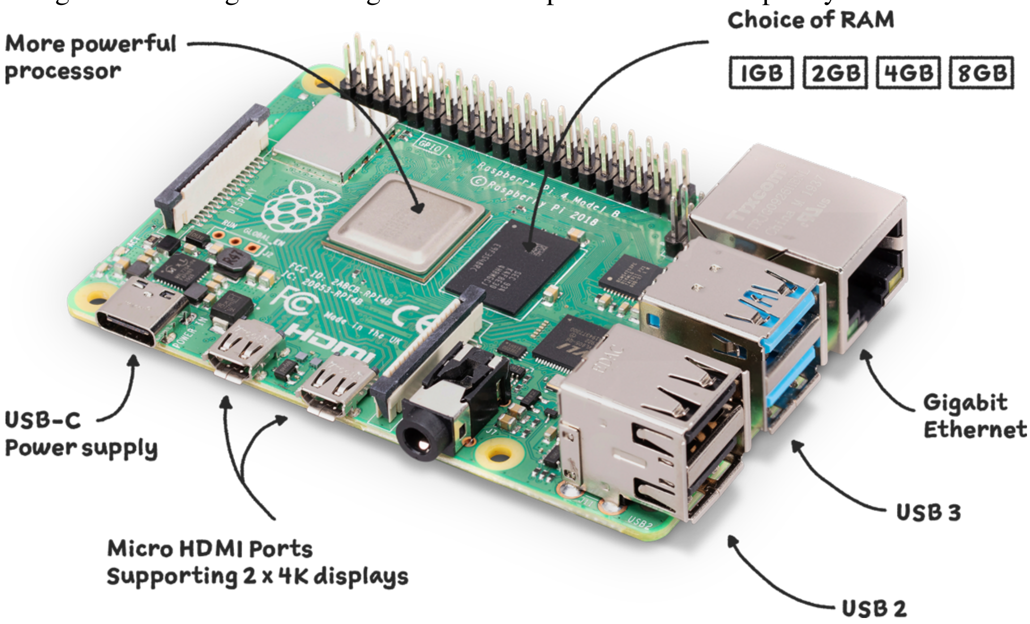


Source: (MORAIS, 2023)

5.2 Experiments Environment

The design of the AAL monitoring system was planned to enable execution on a compact computing platform, such as the Raspberry Pi 4 Model B. Figure 5.2 illustrates some of the single-board computer components. Equipped with up to 8 GB of Memory and powered by a Quad-core ARM Cortex-A72 CPU, this device provides an efficient and robust platform for the AAL system (RASPBERRY. . . , 2023). The intention behind this approach is to foster a seamless integration between the AAL system and the existing hardware in the smart home, thereby facilitating a more accessible and user-friendly experience without compromising the system's performance or capabilities.

Figure 5.2 – Image describing the main components of the Raspberry Pi 4 Model B



Source: (RASPBERRY. . . , 2023)

In order to execute the application within a Docker environment, the system configuration was established mirroring the specifications analogous to those of a Raspberry Pi. Specifically, 8 GB of Memory and a 4-core CPU (Central Processing Unit) were provisioned within this Docker framework. This setup allows for the CPU usage percentage to potentially escalate to 400%, a conventional metric in multi-core systems, where each CPU core contributes 100%.

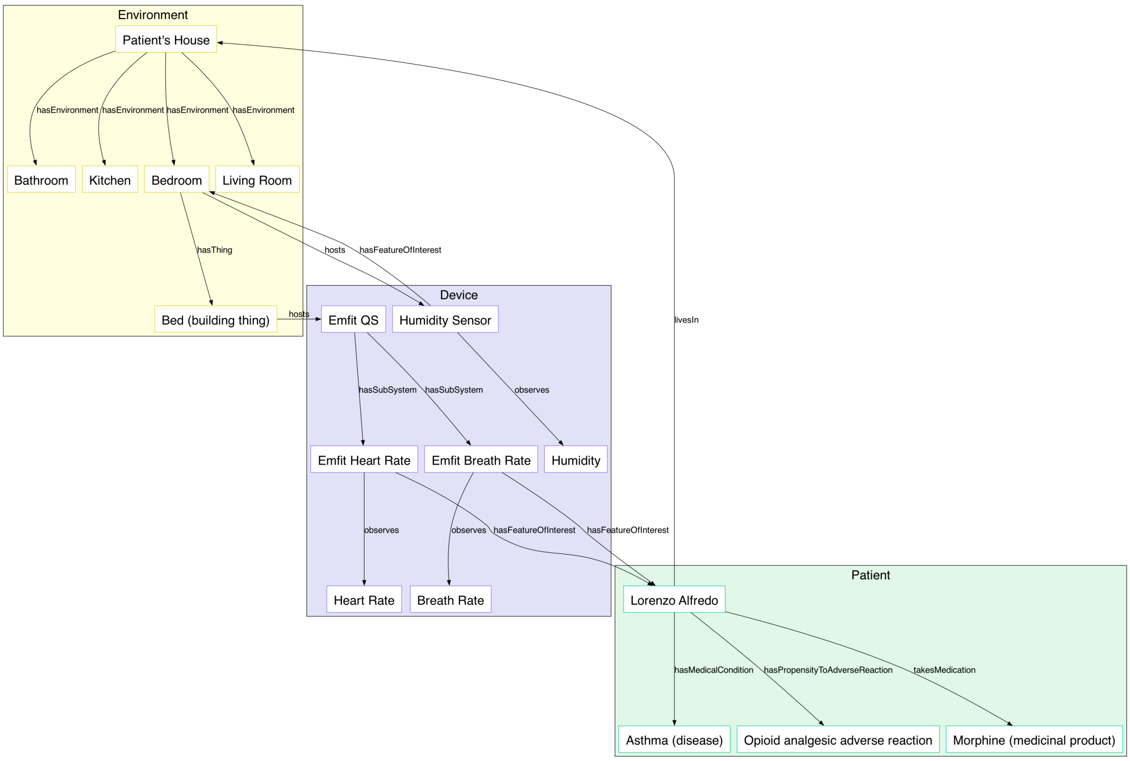
The utilization of resources within this environment is transparent and easily observable, as the services are encapsulated within individual containers. By employing the *Docker Desktop* tool, it can monitor various resource consumption metrics, including CPU and memory usage, disk read and write operations, and network input/output (I/O).

5.3 Use Case Ontology Modeling

The first step to enable the system to function is modeling its ontology instances, defining the patient, environment, and device information. The *Protégé* tool was utilized to instantiate the patient data, environments, and devices intended for use. For the use case, a fictitious patient named *Lorenzo Alfredo* was defined. The environment was modeled based on the HINT environment. In the devices domain, the focus was on selecting specific ones to simplify the test and allow for a controlled environment.

Among all the existing sensors in the apartment, some were selected to be used as sources of information for the tests. The *Emfit QS (Quantified Sleep)* is a device that consists of different sensors, including heart rate and respiratory frequency, which will be the primarily used ones. Figure 5.3 provides a simplified view of the final ontology modeled, divided in the three subdivisions, but connected by the defined relationships.

Figure 5.3 – Use case ontology instance illustrating the experiment configuration of the environment, device and patient fields



Source: The author

5.4 Configuration

To set the AAL System, three main steps should be done: loading the ontology file with the previously instantiated patient, devices and environment data; defining the medical rules; and configuring the connection with Home Assistant.

5.4.1 Loading the Ontology with instances

With the ontology instantiated in Section 5.3, it is now necessary to import it into the system so that the information can be utilized. To accomplish this, the ontology will be loaded in the Turtle format (*.ttl*), which can be easily exported by the *Protégé* tool in a single file. The ontology will be stored in the directory named *fuseki* with the name *aal-ontology.ttl*. By doing so, the system will automatically load it into the RDF graph and be able to interact with it. The ontology's location or URL can easily be configured via an environment variable.

5.4.2 Defining the Medical Rules

Another important step is to define the medical rules. These rules are the core of the system's usefulness and need to be defined by a domain expert, in this case, a health professional. The rules determine the clinical findings that can be discovered. These determinations may include both generic rules, which apply to any patient, and specific rules tailored to the individual patient.

In Listing 5.1, a SWRL rule named "TachycardiaRule" is presented. This rule is structured to infer a clinical finding of tachycardia, a condition where the heart rate exceeds 100 beats per minute. The rule operates as follows: if there exists an observation (?o) that measures heart rate (identified by the SNOMED CT code 364075005), and the result of this observation (?r) exceeds 100, then the associated patient (?p, identified by the SNOMED CT code 116154003) is deduced to have a clinical finding of tachycardia (represented by the SNOMED CT code 3424008). Additionally, the observation itself is tagged as having inferred the condition of tachycardia. This rule exemplifies how semantic web technologies can be employed to derive clinical insights based on observational data.

Listing 5.1 – Tachycardia rule in Jena format, inferring a tachycardia clinical finding based on the observation

```
# Tachycardia: heart rate is above 100
# HeartRate = 364075005
# Tachycardia = 3424008
# Patient = 116154003

[TachycardiaRule:
    (?o rdf:type sosa:Observation)
    (?o sosa:observes sct:364075005)
    (?o sosa:hasSimpleResult ?r)
    greaterThan(?r, 100)
    (?p rdf:type sct:116154003)
    ->
    (?p :hasFinding sct:3424008)
    (?o :inferred sct:3424008)
]
```

Source: The author

In the experiments, some rules have been written for the hypothetical patient. Related to the heart rate there are two rules defined to determine if the patient is experiencing Tachycardia, when the heart rate is faster than expected, or Bradycardia, when the heartbeats are at a lower rate than they should be. Even though the rules may not seem readable, the definitions from SNOMED CT (represented in the file as *sct*) can easily be incorporated into an auto-completion, easy-to-use input interface, using a terminology server like *Hermes* (WARDLE, 2023).

5.4.3 Connecting with the Smart Home Hub

The AAL system was configured integrating it to the Home Assistant that was already connected to the existing devices, such as the *Emfit QS*. To enable the connection of the AAL System and the Home Assistant there are three requirements:

- Both systems need to be connected to the same network.
- Home assistant API needs to be enabled.
- The Home Assistant Long-Lived Access Token should be set as an environment variable on the environment running the AAL System.

Upon executing the AAL system, it should automatically connect to the smart home hub and receive all device information.

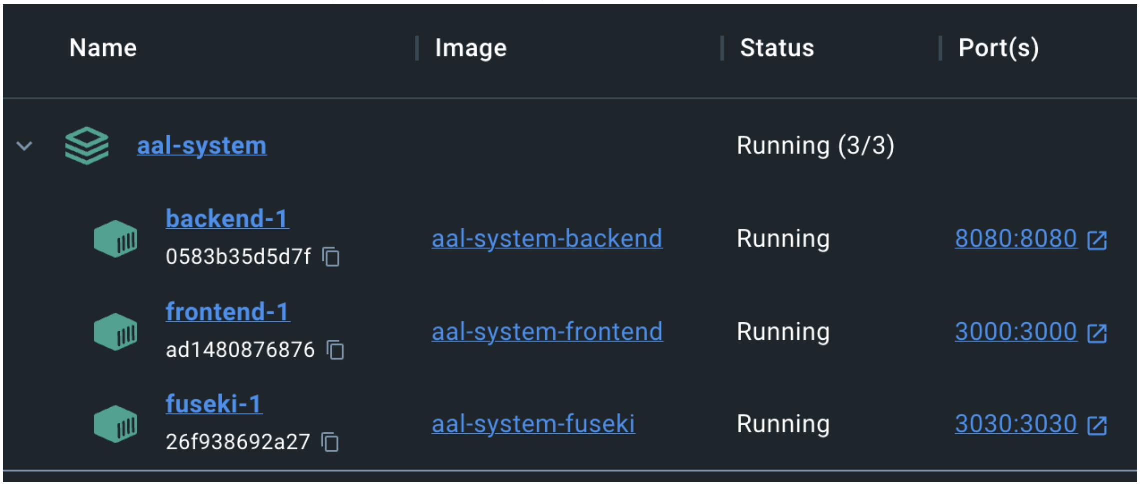
5.4.4 Starting the system

To effectively operate the AAL health monitoring system, which includes the Apache Jena Fuseki server with the specified ontology, the Golang backend system interconnected with the Home Assistant, and the web UI for viewing observations and findings, a single command should be executed:

```
$ docker-compose up
```

The system is neatly containerized, with each of the three services running in its own container. Dependencies between services are pre-configured, and ports are exposed to facilitate inter-service communication. It is possible to visualize it using *Docker Desktop*, as seen in Figure 5.4. Other containers run in this environment but are not relevant to the main proposal, so they will be further explained in Chapter 6.

Figure 5.4 – Running AAL System containers



Source: The author

With the system operational, it is possible to review the logs, particularly those from the backend service, to ensure that sensor states are being received and processed correctly, as illustrated in Figure 5.5, that shows the logs indicating new observations being inserted in the database and events being triggered in the case of values that match the defined rules. Additionally, accessing the web UI will provide the means to view the results. Th

Figure 5.5 – AAL System logs showing the value received by *Emfit* heart rate sensor inferring the Tachycardia finding

```
INFO[0000] Starting AAL System
INFO[0000] Connected to Home Assistant
INFO[0000] Connected to SPARQL
INFO[0000] Starting AAL System
INFO[0000] Inserted observation: sensor=emfit_heartrate value=78.441 (71.816ms)
INFO[0000] Got initial state of all sensors
INFO[0018] Inserted observation: sensor=emfit_heartrate value=80.149 (37.680708ms)
INFO[0018] + Event triggered: tachycardia
INFO[0048] Inserted observation: sensor=emfit_heartrate value=83.238 (10.494375ms)
INFO[0048] + Event triggered: tachycardia
INFO[0078] Inserted observation: sensor=emfit_heartrate value=76.197 (41.512125ms)
INFO[0108] Inserted observation: sensor=emfit_heartrate value=84.009 (20.015791ms)
INFO[0108] + Event triggered: tachycardia
INFO[0138] Inserted observation: sensor=emfit_heartrate value=77.753 (13.965209ms)
INFO[0168] Inserted observation: sensor=emfit_heartrate value=83.986 (12.494875ms)
INFO[0168] + Event triggered: tachycardia
INFO[0198] Inserted observation: sensor=emfit_heartrate value=84.119 (23.8225ms)
INFO[0198] + Event triggered: tachycardia
INFO[0228] Inserted observation: sensor=emfit_heartrate value=72.793 (13.585834ms)
INFO[0228] + Event triggered: bradycardia
INFO[0258] Inserted observation: sensor=emfit_heartrate value=75.481 (35.51925ms)
INFO[0288] Inserted observation: sensor=emfit_heartrate value=77.734 (21.315083ms)
INFO[0318] Inserted observation: sensor=emfit_heartrate value=68.383 (51.687917ms)
INFO[0318] + Event triggered: bradycardia
```

Source: The author

5.5 Usage

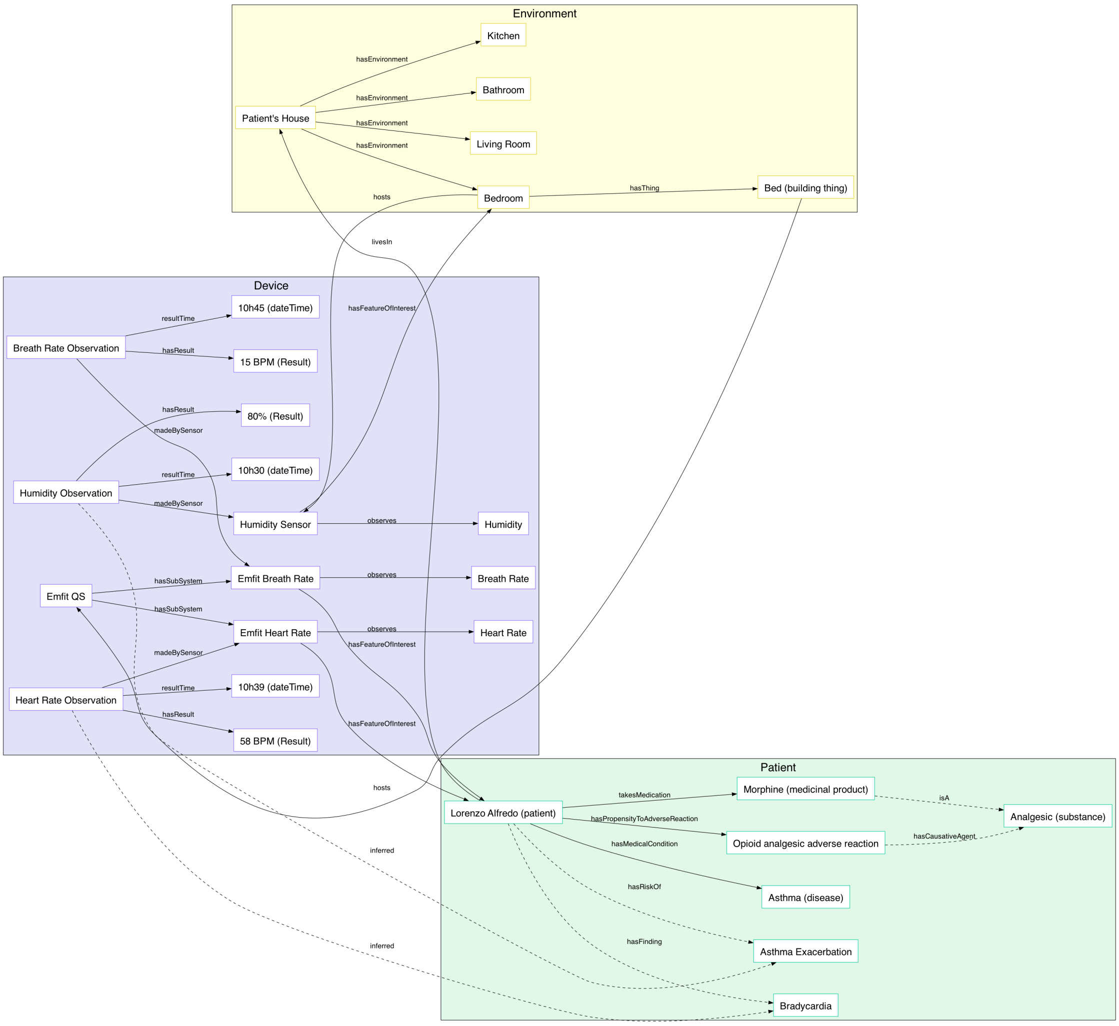
Once the system is installed and configured, the usage is trivial. The device's data will automatically be retrieved by the AAL System and processed. On the Web UI, it is possible to see the observations for each of the properties observed on the right side of the screen, and on the left, it is possible to see the inferred clinical findings, based on the context and sensors' real-time data. With this information, the health professional can proceed with an adequate response to the situation.

In the current test, data was sourced from the Home Assistant's simulated sensor feature, which returns a time-varying signal $V(t)$ every 30 seconds as defined by Function 5.1. This function characterizes a sensor's output using parameters such as mean value (M), amplitude of periodic contribution (A), initiation time (t_0), data generation instance (t), cycle span (w), phase offset (P), and Gaussian noise distribution ($N(s)$). This feature facilitated the emulation of various scenarios through sensor data simulation, proving particularly useful for replicating environments with an increased sensor count.

$$V(t) = M + Asin((2pi(t - t_0)/w) + P) + N(s) \tag{5.1}$$

With the system running, new instances and associations are generated, both from the data inserted by the AAL System, retrieved from the sensors, and from new information inferred from the existing ontology. In Figure 5.6, a simplified representation of a given state of the RDF graph is shown, where the observations that were inserted and the new information that was inferred can be seen.

Figure 5.6 – Use Case with observations and inferred information



Source: The author

It can be observed that the bradycardia finding was inferred from the heart rate observation value. Furthermore, the system identified a risk of asthma exacerbation, based on the fact that the patient has asthma and the humidity sensor recorded an observation of 80% humidity.

5.6 Scalability Experiments

Beyond the tests delineated in the preceding sections, an array of evaluations was conducted on the complete AAL System. These assessments were designed to encompass performance metrics and analyze resource consumption. A series of distinct controlled experiments were executed to achieve this, each one introducing variations in two principal factors: the number of sensors and the number of rules. A modification in the number of sensors contributes to a considerable increase in events from the smart home hub, necessitating augmented backend processing to deliver observations to connected clients. This growth in data requires an enhanced utilization of reasoning capabilities to interpret incoming information, thereby generating pertinent clinical insights.

Table 5.1 – Test cases and variations in the number of sensors and rules

Test No.	No. of Sensors	No. of Rules
1	1	1
2	10	10
3	25	25
4	50	50
5	100	100
6	200	200
7	1	200
8	200	1

Source: The author

The factor adjustments to the number of rules, while not influences the data volume, significantly impacts the reasoning process. This necessitated the execution of multiple inference rules throughout the entirety of the database. Table 5.1 details the various tests performed, reflecting the variations in the factors which increase in the same quantity, as it makes sense to, when more sensors are added more rules will be used. The extreme cases of using a proportion of 1 to 200 in both ways is to evaluate the impact of sensors and rules increases separately. Each test spanned a duration of 4 hours, providing a substantial window to observe, analyze, and document all relevant parameters and outcomes. This systematic approach to experimentation facilitated a thorough exploration of the system's performance and resource utilization across a range of scenarios and scales.

Adjusting the number of rules, while not impacting data volume, significantly affects the reasoning process, requiring the application of multiple inference rules across the entire database. Table 5.1 lists the specific tests, emphasizing variations in factors that increase proportionally. This is consistent with the understanding that the incorporation of additional sensors would logically demand more rules. The extreme scenarios, utilizing a ratio of 1 to 200 in both aspects, aim to analyse the effects of augmenting sensors and rules independently. Each test spanned four hours, providing a window for detailed observation, analysis, and recording of relevant metrics and outcomes. This testing methodology allowed an evaluation of the system's performance and resource usage across various conditions and scales.

6 RESULTS

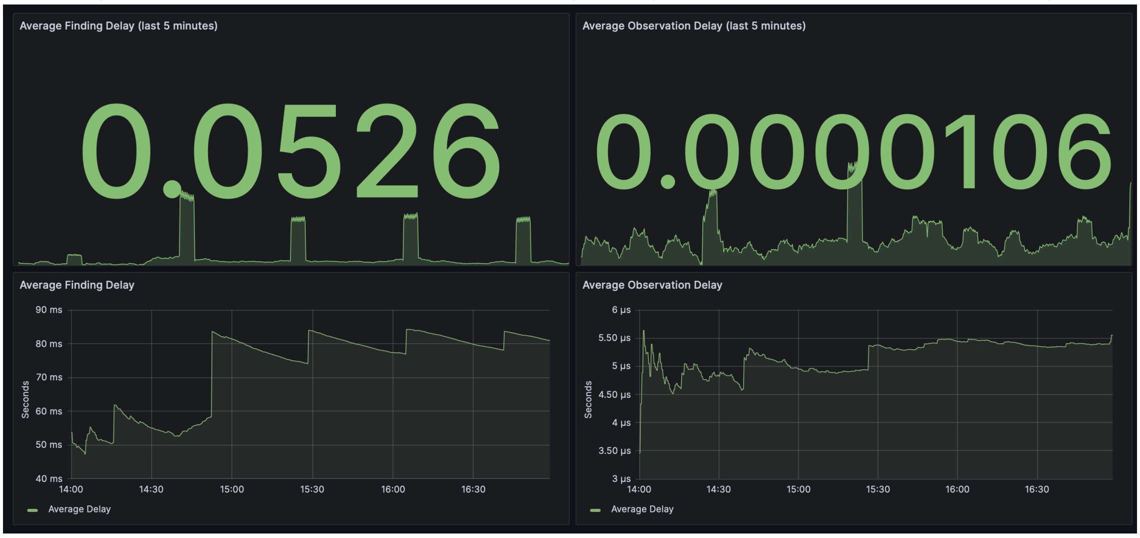
This chapter aims to present the results obtained from the experiments described in Chapter 5, followed by an analysis and interpretation of the results, discussing the possible causes and consequences of what was observed.

6.1 Performance

To effectively monitor system metrics, the capabilities of Prometheus and Grafana tools were integrated within the AAL system, deploying them as containers that operated as part of the system. Prometheus, an open-source monitoring system, played a role in capturing performance metrics. With its data collection mechanisms and versatile querying language, Prometheus facilitated real-time tracking of key system indicators.

Grafana complemented Prometheus by serving as a tool for visualizing and interpreting metric data. As a data visualization platform, Grafana allowed for the creation of personalized dashboards and interactive graphs, transforming complex metric datasets into visual insights. The combination of Prometheus and Grafana provided efficient metric collection and analysis. Figure 6.1 shows one of the dashboards created in Grafana UI to monitor the delay of observations and findings generation from the events received from the home automation platform, using the Prometheus server as the data source.

Figure 6.1 – Grafana dashboard with average delay time for observations and findings



Source: The author, from Grafana UI

In assessing performance metrics for the Ambient Assisted Living (AAL) system, the focus was placed on delay times associated with two specific events: observation and finding. The *observation delay* metric measures the time interval between the reception of an event from the smart home hub and its transmission to the client. In parallel, the *finding delay* measures the duration between receiving an event from the home assistant and the subsequent transmission of the clinical finding, as inferred by the system, to the client. To facilitate this analysis, system rules were modified to consistently generate a new finding for a designated sensor. As a result, every new event from that sensor triggers the creation of a finding and naturally also an observation.

Table 6.1 – Time delay from receiving of a new event to generating observations and clinical findings

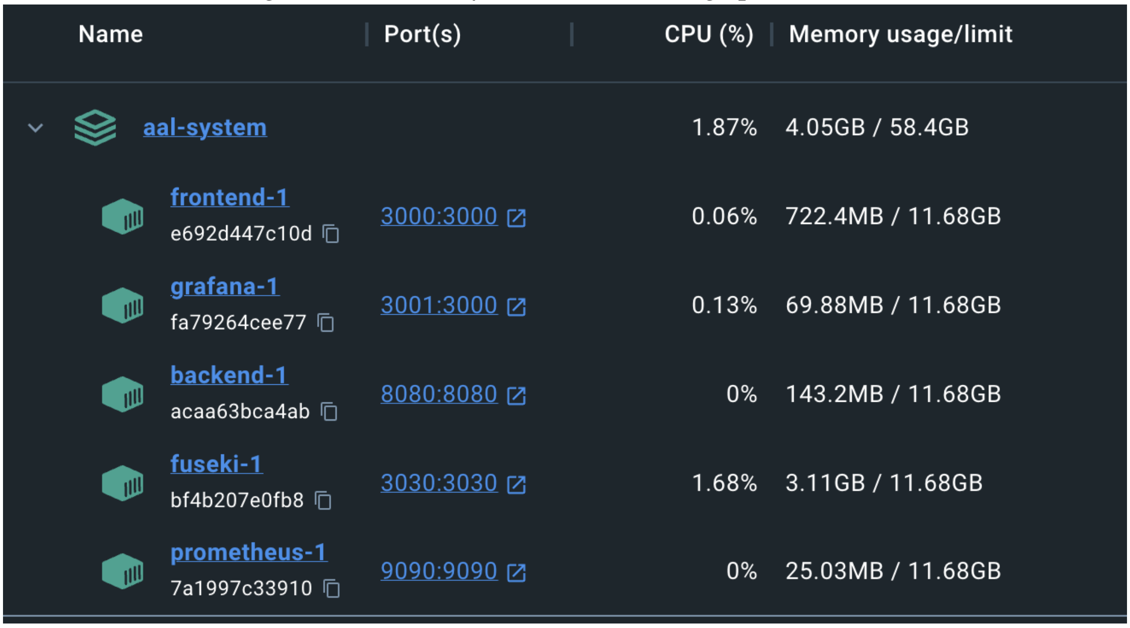
Test No.	**Observation Delay** (μs)	**Finding Delay (ms)**
1	4.710	56.227
2	7.963	103.400
3	7.802	104.813
4	9.093	104.141
5	15.829	112.640
6	16.647	207.740
7	5.475	67.192
8	7.309	117.243

Source: The author

6.2 Resources

In order to monitor the system resource consumption, the Docker Desktop platform was employed, facilitating real-time visualizations of CPU, memory, network, and I/O utilization, as seen in Figure 6.2. For a more in-depth, impartial analysis and experimentation, the Docker client Python library was utilized and integrated into a script to systematically gather usage data, ultimately generating pertinent statistics like average utilization, as outlined in Tables 6.2 and 6.3. Primarily, CPU and memory were the main attributes observed, given their important role and constraining impact in this specific application context.

Figure 6.2 – AAL System resources usage per container



Source: The author, from Docker Desktop

6.2.1 Resources usage in SPARQL and Reasoning Server

The analysis of resources employed by the SPARQL and Reasoning server, as detailed in Table 6.2, highlights the escalation in CPU usage, but mainly the increase memory consumption corresponding to an increase in the number of sensors and rules. However, the study also reveals that the resources utilized remain within acceptable limits, especially considering that an Ambient Assisted Living environment typically encompasses no more than 25 sensors. Particularly with regard to CPU usage, which is the resource most notably affected, the increase in utilization remains modest even with 200 sensors. On average, this does not reach even half of the total capacity, indicating that the system operates within a sustainable threshold.

Table 6.2 – Resources Usage for the SPARQL and Reasoning Server

Test No.	Memory (GB)	CPU (%)
1	4.72	3.21
2	5.36	5.22
3	6.02	7.11
4	5.48	18.29
5	3.30	32.35
6	3.94	120.96
7	4.05	3.19
8	6.75	74.38

Source: The author

6.2.2 Resources Usage in AAL Backend Service

The Backend server demonstrates a remarkable efficiency in resource consumption, encompassing both CPU and memory, even when operating in an environment with as many as 200 sensors. It is interesting to note that the usage of both these resources does not increase significantly with the escalation in the number of sensors and rules. As delineated in Table 6.3, this low level of resource utilization not only showcases the server's robust capability to manage hundreds of concurrent events without difficulty but also affirms its operational effectiveness. This finding underscores the system's potential for scalability and its readiness to meet more demanding conditions if required.

Table 6.3 – Resources usage for the Backend

Test No.	**Memory (GB)**	**CPU (%)**
1	0.24	0.63
2	0.20	1.04
3	0.21	0.99
4	0.19	1.21
5	0.25	1.04
6	0.24	1.31
7	0.24	0.56
8	0.25	1.84

Source: The author

Table 6.4 – Summary of all results of resources usage and time delay, by variations in the number of sensors and rules

Test No.	**No. of Sensors**	**No. of Rules**	**Backend**		**SPARQL**		**Observation Delay** (μs)	**Finding Delay (ms)**
			Memory (GB)	**CPU (%)**	**Memory (GB)**	**CPU (%)**		
1	1	1	0.24	0.63	4.72	3.21	5.622	47.109
2	10	10	0.20	1.04	5.36	5.22	7.963	103.400
3	25	25	0.21	0.99	6.02	7.11	7.802	104.813
4	50	50	0.19	1.21	5.48	18.29	9.093	104.141
5	100	100	0.25	1.04	3.30	32.35	15.829	112.640
6	200	200	0.24	1.31	3.94	120.96	16.647	207.740
7	1	200	0.24	0.56	4.05	3.19	5.475	67.192
8	200	1	0.25	1.83	6.75	75.38	7.309	117.243

Source: The author

7 ANALYSIS AND DISCUSSION OF EXPERIMENTAL RESULTS

This chapter aims to present a discussion about the experiments presented in Chapter 5 and an analysis and interpretation of the results presented in Chapter 6, discussing the possible causes and consequences of what was observed.

7.1 Analysis of the proposed AAL Ontology

The developed Ambient Assisted Living ontology aims to comprehensively encompass the domain, addressing IoT devices, Smart Home attributes, patient health metrics, and specific elements of the medical field. Its integrated nature ensures the representation of disorders, medications, procedures, and beyond, facilitating the creation of rules aligning with medical terminologies and promoting inference based on the relationships among various concepts. Additionally, by employing medical codes to denote domain terms, the ontology ensures seamless integration with existing medical systems and also facilitates the data internationalization across systems that use of this ontology.

The AAL ontology was designed to be both straightforward and extensible, enabling practical applications. For individuals familiar with how ontologies function, managing this specific one should be accessible, especially since it uses existing standards and incorporates established concepts across all domains it covers. The development of the AAL monitoring system demonstrates the practical usage in real-world projects, validating its relevance.

The extensive scope of the AAL ontology also presents challenges due to its size, especially by the integration of the SNOMED CT ontology, which encompasses thousands of clinical terms, ranging from patient social context nomenclatures to medications and medical procedures. Such inclusiveness makes the ontology both voluminous and complex. To mitigate these challenges, it could be considered to use a subset of the SNOMED CT ontology, focusing on entities pertinent to the AAL domain, even though delineating what is relevant can be difficult.

7.2 Discussing the AAL Monitoring System

The Ambient Assisted Living monitoring system exhibited a great performance, surpassing our initial expectations. The following subsections will present a brief discussion of various aspects of the system. This analysis is informed by our empirical observations drawn from our experiments, as well as the expectations and hypotheses that framed our understanding of the solution.

7.2.1 Installation and Configuration of the AAL System

To be able to run the AAL system, the first step was to install and configure it. The installation process for the AAL system has been simplified through the utilization of *docker-compose*, a tool designed for running multi-container Docker applications (INC., 2023). The prerequisites are minimal, primarily due to the containerization approach, making the system executable with just Docker installed on the machine. Configuring the Home Automation Platform is straightforward; one only needs to obtain the access token and activate the API in the already operational Home Assistant. With clear instructions, both tasks can be accomplished by a user who, while not an expert, is familiar with tech environments.

The most challenging aspect of the setup pertains to ontology instantiating. Even with the aid of renowned tools like *Protégé*, the process is not intuitive for those unfamiliar with ontologies. This can be a big challenge. Proper instantiating requires a deep understanding of the ontology, including its object properties and the relationships that need to be established. Facilitating this process should not be overly complicated, even though it is outside the scope of this project. The development of a user-friendly frontend that guides users on how to add sensors, environments, and further sensors to the ontology, in conjunction with an auto-completion tool, can make this process both rapid and precise.

In summary, as depicted in Figure 7.1, the configuration process entails three principal sequential steps. First, the ontology is initialized, tailored to the intended installation settings, which encompass patient data, sensors, and the physical environment. Second, medical rules are established to facilitate the inference of clinical findings. Lastly, the AAL system is integrated with the smart home hub.

Figure 7.1 – AAL Configuration Steps

Source: The author

7.2.2 Usage

The monitoring system is user-friendly and has been strategically crafted to facilitate the connection of new clients for data consumption. It permits integration with third-party systems or UI client connections, thereby enhancing the visual interface. This design not only offers insightful health data to professionals but also extends accessibility to the patients being monitored, fostering a more personalized and broad understanding of their health status.

The frontend, developed as a demonstration of the system's capabilities, holds potential for further refinement, that could encompass a more expansive display of statistics, trends, alerts. More than that, the system could be improved for taking automated actions based on the current health state of the patient and its surrounding environment.

The integration of sensors is made easy and efficient through the utilization of the Home Automation Platform, serving as a lower-level layer that ensures connection with diverse devices and standardization of incoming data. This design contributes to the system's modularity and clarity of responsibilities, allowing the system to focus on implementing AAL-specific concepts. By doing so, the system is relieved from the complexities of lower-level communication with the IoT devices, enhancing its focus and effectiveness in its primary responsibilities.

The integration of sensors is facilitated and made efficient through the use of the Home Automation Platform, acting as a lower-level layer that ensures connection with a variety of devices and standardizes the incoming data. This design enhances the system's modularity and delineation of responsibilities, allowing for a concentrated focus on implementing AAL-specific concepts. Consequently, the system is doesn't need to handle the complexities of lower-level communication with the IoT devices, augmenting its focus and effectiveness in fulfilling its primary responsibilities.

7.2.3 Performance

In the conducted experiments, detailed in Chapters 5 and 6, the system's startup time in all situations took less than one minute, a duration considered minimal. Notably, at least 90% of this starting time was due to the backend system waiting for the Fuseki server to initialize and allow connection.

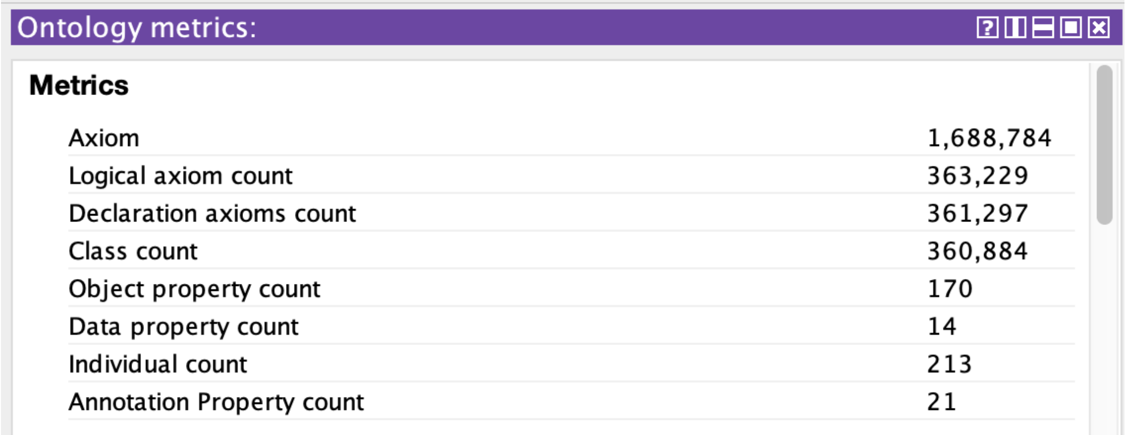
Once operational, the system exhibited performance metrics with an average response time of 207.46 milliseconds in the worst-case scenario. This metric is notable when compared to the average human reaction time to a visual stimulus, which is approximately 230 milliseconds (JAIN et al., 2015). Such rapid responsiveness qualifies the system for real-time monitoring applications for healthcare professionals. However, for tasks involving more nuanced health-related actions, the suitability of the system for real-time performance would need to be assessed on a case-by-case basis.

7.2.4 Resources

Upon examining the container's resource usage from the previous chapter, it becomes evident that among the three containers, the Apache Jena Fuseki server consumes the most resources. This server operates the entire ontology graph and the inference engine. A closer look at the server reveals that the network, disk, and CPU usage are relatively low for such an application. While the level of memory usage may limit the selection of compatible devices for system installation, it is worth noting that it is a reasonable range for the intended hardware profile. As a result, although the memory requirement is significant, it aligns with the system's design goals and does not detract from its feasibility or effectiveness in the envisioned application context.

To reduce the memory usage of the SPARQL and reasoning server, multiple strategies can be explored. However, the primary approach that may aid in this reduction, without diminishing the efficacy of the ontology in fulfilling its role as an AAL base, involves optimizing the size of the ontology. This size is considerable due to the inclusion of all imported entities from SNOMED CT, encompassing approximately 360,000 classes and around 1,688,000 axioms, as it can be observed in Figure 7.2. It increases the complexity of the model and especially the reasoning process. By targeting this aspect, potential optimizations could be achieved without compromising the underlying purpose and power of the ontology.

Figure 7.2 – AAL Ontology metrics



Ontology metrics:

Metrics

Axiom	1,688,784
Logical axiom count	363,229
Declaration axioms count	361,297
Class count	360,884
Object property count	170
Data property count	14
Individual count	213
Annotation Property count	21

Source: The author, from Protégé

The backend system's resource utilization is elucidated by Figure 7.3. Initially, there's a noticeable spike in CPU usage; however, it stabilizes to a minimal level subsequently. Memory consumption remains consistently low throughout the operation. As anticipated, Network I/O demonstrates a steady increase, attributable to the continuous influx of data from the smart home hub and the ongoing transmission of observations and findings to the client.

Figure 7.3 – Backend container resources graph demonstrating the CPU, memory, disk read/write and network I/O usage

Source: The author, from Docker Desktop

The backend system could be a point of stress, given that it receives all data from the home automation platform, handles it, sends multiple queries to the SPARQL server and serves the WebSocket API. But as demonstrated, it handles it in an efficient way, consuming really low resources. The reason for that is probably because of the effective way of using concurrent features provided by the Go programming language and the event-based architecture of the system, just acting upon a new event, not depending on any polling strategy or any other operation that could lead to inefficient processing.

The frontend container only builds the image and serves the files, so it clearly is not a point of concern. The frontend is responsible for establishing a WebSocket connection with the backend system and showing the results in a user-friendly way.

8 CONCLUSION AND FUTURE WORK

This chapter summarizes this study, using the results from Chapter 6 and the analysis done in Chapter 7 to verify the main contributions of the current study. Finally, future work directions are suggested.

8.1 Contributions

The fusion of Smart Home technologies with healthcare presents a new approach to home healthcare, catering to the escalating needs of our ageing global population. This study introduces a novel ontology that seamlessly integrates IoT and Smart Home ontologies with the renowned healthcare ontology, SNOMED CT. This robust and adaptable AAL ontology lays the foundation for knowledge sharing and paves the way for the development of systems built upon it.

Proving this, our research has demonstrated an ontology-centric health monitoring software that bridges the gap between IoT devices within smart homes and the healthcare sector, utilizing the proposed ontology as its cornerstone. This methodology guarantees semantic interoperability, providing a more customized healthcare delivery. It aids healthcare providers in efficiently monitoring and addressing the needs of patients, especially the elderly and those with chronic conditions.

Empirical tests conducted in the Halmstad Intelligent Home further attest to the system's practicality and efficacy. As the quest for home healthcare solutions intensifies, our findings highlight the significance of ontology-driven systems, especially in intricate domains like AAL, to deliver personalized, patient-focused care within the comfort of the patient's home.

8.2 Future Work

In future works, an area of focus will be the integration with Electronic Health Record systems. This integration aims to automate the collection of medical data, ensuring a seamless flow of information and enhancing the system's autonomy, eliminating the need for manual insertion of new medical conditions or medication intakes.

In future research phases, it would be interesting to conduct further tests and validations with actual users under the supervision of healthcare professionals. This would provide deeper insights into system usability and potential enhancements for utilization. Moreover, assessments targeting specific system components, such as potential data loss from the smart home hub, could offer a more comprehensive validation. A notable route for optimizing system resource consumption is reducing the ontology size, as elaborated in Chapter 7.

Additionally, enhancing the system to enable SWRL rule management through a REST API will be prioritized. This will not only facilitate the process of creating, modifying, and activating/deactivating rules but also ensure a more user-friendly interface for healthcare providers and system administrators.

Creating a database of generic rules, not tailored to specific users, could improve processes by eliminating the need for individual rule implementation for every patient when not necessary. Moreover, introducing a feature that recommends rules derived from the current environment, sensors installed, and patient details could substantially augment system usability. The integration of an artificial intelligence (AI) model, leveraging the defined ontology settings for rule generation, represents a promising enhancement to the system's capabilities.

Lastly, to expedite the deployment in new environments, we envision the development of a frontend software that leverages the usage of a terminology server, simplifying the instantiating process and ensuring a more intuitive user experience. These advancements will undoubtedly elevate the system's functionality and user adaptability, pushing the boundaries of personalized home healthcare solutions.

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