Systematization of Knowledge of Ambient Assisted Living Systems: A Privacy Perspective

Md Sakib Nizam Khan[*†], **Sonja Buchegger**[**‡]

[†,‡]Division of Theoretical Computer Science, KTH Royal Institute of Technology, Stockholm, SE-100 44, Sweden.

E-mail: msnkhan@kth.se, buc@kth.se

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Abstract. The confluence of several developments make privacy of ambient assisted living (AAL) an increasingly important problem: aging population, scale and availability of sensors (IoT, health monitoring, smart home) leading to higher quality and quantity of sensitive data, and advances in data analysis and learning. Privacy research has not been in sync with these developments. For AAL systems to be useful and used, they need to be trustworthy and protect the users' privacy. We conducted a systematic literature review on recent AAL research to provide a map for potential privacy concerns. We also collected already available commercial systems for a comparison with those found in the academic literature. We were able to distill a common architecture covering most commercial and academic systems, including an inventory of what concerns they address, the technologies they apply, their data handling, and privacy considerations. Based on this outcome, we identified potential intervention points for privacy.

Keywords. health monitoring, ambient assisted living, smart home, IoT, privacy

1 Introduction

In recent years, the world's elderly population has seen gradual growth, and demographers predict a 70% increase by 2050 in developed regions of the world [152]. The proportion of the elderly population is estimated to be around 20-25% of the total population by 2050 globally [12]. This global phenomenon introduces new challenges in society and ensuring proper healthcare for the older population is one of them. For the latter, we need extra resources (e.g. caregivers, doctors) and facilities (e.g. hospitals, equipment). Additionally, the Covid-19 pandemic has shown the need of more and better means to ensure healthcare while maintaining a certain required distance. For instance, in countries like Sweden, the mortality rate due to Covid-19 was exceedingly high in elderly care homes with multiple inhabitants.

At the same time, the advancement in information and communication technology has enabled paradigms such as the Internet of Things (IoT) which in turn facilitates services such as remote health monitoring and Ambient Assisted Living (AAL) for tackling these challenges.

The Internet of Things (IoT) paradigm aims to connect objects surrounding us, from tiny sensors to big industrial equipment, refrigerators, doors, cars, light bulbs, etc., to the Internet. The paradigm facilitates novel applications in different domains such as healthcare, ambient intelligence, smart homes, smart cities, and smart grid [33]. The idea of ambient intelligence is to build a context-aware intelligent environment that can automatically adapt itself to dynamic needs of the user [29]. Based on this concept, many different ideas have emerged and home-based remote healthcare for the elderly also termed Ambient Assisted Living (AAL) is one of them.

AAL is defined as the utilization of information and communication technologies in an individual's daily life and work environment for enabling independent living in their old age [1]. AAL systems generally deploy sensors to collect user's health and surrounding environment data which is then used by the stakeholders such as the person in the AAL environment (henceforth termed the user), caregivers, hospitals, doctors, and family members for monitoring and ensuring the user's well-being. The ability of continuous monitoring through uninterrupted data collection is the key enabler for AAL technology. Nevertheless, the health and environmental data collected by AAL systems are privacy-sensitive. Thus, ensuring the security and privacy of the data is a must for these systems. However, doing so is not straightforward due to their unique characteristics, such as the need for continuous monitoring, target user groups of elderly people and corresponding usability requirements, the critical importance of data accuracy impeding measures that add noise, and the variety of stakeholders that need access to the data. For such reasons, privacy is considered one of the key challenges for AAL technology [70].

AAL systems are diverse in nature due to the heterogeneity of the devices involved. They have different vendors, varying capabilities, and also distinct characteristics. For instance, small sensors such as motion sensors or door sensors have limited energy and processing power whereas smart cameras, smart microwaves, or fridges are not limited by batteries and have more processing power. This diversity makes it difficult to analyze issues and propose solutions for AAL systems in general. To systematically address the privacy issues of AAL systems, researchers need to understand the landscape of AAL. Though numerous research efforts are focusing on AAL systems, they are scattered. The community needs a clear understanding of the current research literature as well as existing commercial systems to identify potential privacy and security issues and gaps in AAL systems.

In this work, we perform a systematic literature review on AAL systems to identify their research focus and, in turn, their privacy and security considerations. We explain our methodology in Section 2. We systematize the literature based on some distinct categories and discuss the literature across them, in Section 3. We survey commercially available AAL systems in the market in Section 4. We discuss the current privacy and security situation of AAL systems based on our findings in Section 5 and identify potential future research directions concerning the privacy and security aspects of AAL in Section 6. In Section 7, we compare our findings with the state of the art and, finally, we conclude our work in Section 8.

2 Method

Our main **research goal** is to find out about privacy and security concerns in AAL (seeing security as a prerequisite for privacy) both directly, i.e., what the research papers include, and indirectly, by investigating the focus areas of AAL research.

To perform a comprehensive literature review on smart home remote health monitoring systems and their security and privacy concerns, a literature search has been conducted in 2020. We also performed a survey of commercially available AAL systems (see Section 4); here we describe the methodology of the academic literature review.

2.1 Literature Selection

2.1.1 Sources

Our primary focus is computer-science related literature, including the top security and privacy conferences in the field such as ACM CCS, IEEE S&P, PETS, ESORICS, USENIX Security and Euro S&P. IEEE Xplore and ACM mostly consist of computer science-related literature including the majority of the top security and privacy conferences[1]. We also found that the ACM database includes some articles published by Elsevier and Springer. Initially, we considered Web of Science (WoS) and Scopus in our search list alongside IEEE and ACM. However, WoS and Scopus were returning an overwhelming number of articles even after restricting the subject area to only computer science. Thus, to keep the number of articles manageable while still ensuring that our requirements are fulfilled, we ended up choosing ACM and IEEE Xplore. We also performed a manual lookup to the results returned by Scopus and WoS which revealed that the results from IEEE Xplore and ACM is a good representative sample of the results from Scopus and WoS.

2.1.2 Search

For searching the literature, we use combined keywords such as remote health monitoring systems, ambient assisted living, e-health, elderly, and smart home. In each database, the search query ***((("health monitor*" OR "ambient assisted living" OR "e-health") AND (elder* OR senior OR old*) AND ("smart home" OR iot)))*** is entered with some database specific modifications. The search is only performed on the metadata (i.e. Title, Abstract, and Keywords) and not on the full text. The query is generated by looking into how remote health monitoring systems for smart homes are commonly termed in the scientific literature. The initial search results are discussed below:

IEEE Xplore returned 92 papers.

ACM returned 53 results.

No.	Exclusion Criteria - Exclude if the article...	Articles Excluded
1	is not a research article (i.e., talk, keynote, book, workshop introduction, implementation or summary of existing research)	15
2	is irrelevant to our research goal (e.g. concerning medical, hardware research etc.)	10
3	is not written in English	1

Table 1: List of Exclusion Criteria

[1] PETS and USENIX Security are not included in IEEE & ACM and ESORICS is partly included in ACM. As they are very relevant for our survey, we separately checked all three of them but did not find any articles matching our query.

2.1.3 Exclusion Criteria

To select relevant literature that is aligned with our research goal, we constructed a set of exclusion criteria to filter our search results. Table 1 lists our exclusion criteria and the number of articles excluded based on each criterion.

In the first round of screening, we examined the title and the abstract of the articles. If an article matched any of the exclusion criteria in Table 1, it was excluded and included otherwise. In a second round of screening, for when the applicability of exclusion criterion 1 and 2 was not conclusive in the first round, we read the content of the paper and decided after discussion.

In summary, among 145 articles, 15 articles were excluded due to criterion 1; for criterion 2, 10 articles were excluded, and 1 article was excluded for criterion 3. A full list of excluded articles with the reason for exclusion is provided in Table 3 in Appendix A. Besides this, 9 duplicate articles present in both databases were also found and excluded. Thus, after applying the exclusion criteria and removing duplicates, the remaining articles, 110 in total, were chosen for a thorough review.

2.1.4 Limitations and possible extensions

In this literature review, we wanted to have a broad overview of the privacy situation in the field while keeping the number of articles to review at a feasible level. We thus chose to keep a fairly narrow query (in terms of the AAL context but open to any technology) and limited sources to keep the number of papers manageable, though representative, and the process reproducible and modular for easier future extensions. We are aware that the selection process inherent in the systematic literature review, i.e., strictly adhering to the query, does not result in an exhaustive set of works relevant for ambient assisted living but only a slice of what is available. Thus, an interesting future work would be to repeat the methodology on other databases such as Scopus, WoS, Compendex, ScienceDirect, etc., and focusing on the papers not yet included here, for a comparison. In terms of the search query, the work can be extended by modifying the search query to include other related fields or focus on any particular sub-area within the field of AAL.

2.2 Synthesis

For the thorough review of the articles, we constructed several research questions. The questions are as follows:

RQ1 Architecture of the frameworks or systems

- **(RQ1.1)** What kinds of framework or system architecture are being proposed?
- **(RQ1.2)** Is it a centralized or distributed architecture?

Motivation: The architecture of a framework or system is vital for understanding the overall system. In addition, security and privacy implications vary according to the centralized or distributed nature of a system. These questions help us understand the key insights of the proposed systems or frameworks.

RQ2 Technologies used to develop the AAL systems

- **(RQ2.1)** Do the proposed systems or frameworks focus on any particular driving technologies or components?

Motivation: If there are some driving technologies for instance cloud, wireless sensor network, etc. in the proposed systems or frameworks, then we can evaluate the systems based on the known security and privacy limitations of these technologies.

RQ3 Data handling of AAL systems

- **(RQ3.1)** What data is collected (or which sensors are used) by the system?
- **(RQ3.2)** How is the data stored and managed?
- **(RQ3.3)** Is there any security or privacy consideration?

Motivation: Remote health monitoring systems handle and process privacy-sensitive data. Thus, what data is collected and how the data is handled by the system will provide key insights into the security and privacy considerations of the proposed systems which is one of our primary research questions.

Based on these questions, we review each article under consideration. The results of the review are discussed in Section 5.

3 Systematization of Literature

To be able discuss the articles in a structured manner, we distilled prevalent themes from the papers and grouped them accordingly. Conceptualizing ambient assisted living as an application of the Internet of Things helped us come up with intuitive broad categories for a first grouping. If the article was mostly concerned with the Internet part of IoT, it got grouped into the network communication category, if it was more about the Things themselves, we distinguished between how the Thing interacts with the environment (sensor, actuator, user interface) and what it does with the resulting input (data processing). Articles with a holistic perspective, either concerning the whole IoT system or a whole set of systems, were grouped into frameworks and reviews, respectively. The driving factor for this work being privacy and security, which are cross-cutting concerns often connected to business models that depend on the users' data, led us to separate categories for these themes.

Figure 1 presents the main categories and the number of articles that fall into these categories. It is worth noting that the categorizations used here are not mutually exclusive (i.e., a few articles address multiple categories). A full list of articles under each category is provided in Table 4 in Appendix B.

While grouping the articles, we found that within the categories several articles work on similar topics or concerns. Hence, for easier navigation within the categories, we go one step further and group similar articles together into sub-categories.

In the next sub-sections, for each category, we first provide a brief summary of the findings and then discuss the articles in more detail, grouped by their main topics or concerns.

3.1 Frameworks

Summary. *The largest part of AAL research in our survey (48 papers) focuses on defining frameworks or developing prototypes as the field is still relatively young. Among these papers, a major*

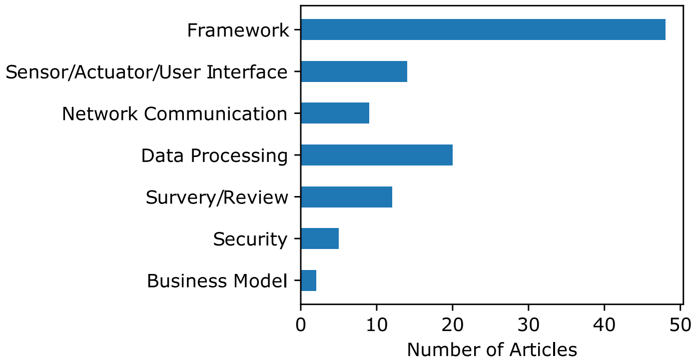

Figure 1: Categorization of Articles Reviewed

share focuses on integrating various technologies such as IoT, cloud, context awareness, etc. into AAL. Apart from this, several other works identified the special requirements of AAL in terms of sensors, hardware, cost, scalability, etc. and proposed frameworks to fulfill the requirements. Additionally, multiple works developed proof of concept prototypes for AAL using commonly available IoT boards such as Raspberry Pi and Arduino.

IoT-based Frameworks. The goal of several frameworks is to integrate e-health and IoT to extend healthcare in various dimensions, namely to improve healthcare in poor countries [40], automate activities of building inhabitants [145], and detect declining health early by monitoring outdoors [53]. Corotinschi et al. [40] proposed an IoT-based e-health system to improve the healthcare system in Romania by making quality medical services available to a larger population with the help of family physicians. A pilot project was implemented on a large scale in the North-East of Romania, which extended the e-health service to 360 thousand individuals, and among them, 42 thousand people were treated using the service. Gaddam et al. [53] developed a smart IoT-based outdoor health-monitoring system for early detection of the declining health of individuals from mobility, posture, and overall gait in public settings such as parks or supermarkets.

Another concern is time sensitivity; frameworks are proposed for models of criticality [84], constant care with social IoT [126], video assistance [162], real-time clinical feedback [106], utilization of passive sensing [52], and multi-level activity monitoring [160], as well as a combination of different IoT technologies [46]. Kotronis et al. [84] focused on identifying and modeling the criticality requirements of IoT-based remote health-monitoring systems by categorizing them into three categories: safety-critical, mission-critical, and non-critical requirements. Nguen et al. [106] explored the usage of IoT-based applications in healthcare and also proposed an IoT Tiered Architecture (IoTTA) that aims for the transformation of sensor data into real-time clinical feedback. Forkan et al. [52] utilize passive sensing for monitoring the health of elderly people in real-time in their homes. They validated their approach by real-world trials, installing the system in the homes of six elderly persons for a period of 1.5 to 4 months. Dohr et al. [46] explored how an AAL paradigm can be realized using different IoT technologies and ended up combining Keep In Touch (KIT) technology and Closed Loop Healthcare.

Technology-based Frameworks. Besides IoT, several research works proposed frameworks based on more specific technologies such as cloud [116, 117, 59], Industrial Internet of Things (IIoT) [70], active database system [43], Narrowband IoT (NB-IoT) [154], and wireless sensor network [92]. Pham et al. [116, 117] proposed a Cloud-based Smart Home Environment (CoSHE) framework for delivering healthcare at home which collects physiological, motion, and audio signals and provides contextual information of the patient in terms of activity and location at home. Based on a case study, the authors show that CoSHE is capable of integrating contextual information into health data and this information facilitates a better understanding of patients' health status. Morais and Wickström [43] proposed a technique to develop a smart environment as an active database system and demonstrated with a smart bedroom that it facilitates a flexible and robust architecture for AAL in smart homes. Wang et al. [154] developed a Narrowband IoT (NB-IoT) technology-based human health monitoring system capable of monitoring the heartbeat, temperature, and location of the patients and sending email alerts in real-time. According to the authors, in the experimental results, the system showed excellent performance in measuring heart rate and GPS position.

Context-aware Frameworks. Involving context in the decision-making process and providing context-aware services has become a de facto standard for most technologies recently and AAL is no different. Multiple research works [113, 144, 69, 104, 103] focused on context-aware frameworks for AAL. A context-aware AAL system by Paola et al. [113] aims to detect anomalies and prevent possible emergencies by analyzing the user's current action, the context, and the user's past behaviors. Hossain et al. [69] proposed a context-aware elderly entertainment support system (CAEESS) in the AAL environment by investigating the entertainment requirements from the perspectives of both the elderly and the caregiver. Nazário et al. [104] presented a context-management framework using Quality of Context (QoC) for enhancing the e-health environment.

Sensors and Hardware-based Frameworks. For AAL systems, sensors and hardware components are one of the essential elements and require some special features besides the generic ones for IoT. Thus, several research works proposed sensing framework [19, 72] and hardware components [17, 71] specifically designed for AAL. Alsibai et al. [17] designed a new electric-powered wheelchair capable of integrating other IoT-based health monitoring devices. Hui and Kan [71] proposed an active Near-field Coherent Sensing (NCS) system which can be integrated into generic seat structures to monitor the heartbeat, respiration, and blood pressure of the person sitting on the seat. The authors also briefly investigated the variations of sensor placement to account for body sizes and concluded that depending on the position of the sensors, the signal-to-noise ratio can vary significantly. A people-centric sensing framework for AAL has been proposed by Hussain et al. [72] which aims to monitor health and provide service-oriented emergency response in case of abnormal health conditions for the elderly in a smart home environment.

Prototypes for AAL. Designing and developing a prototype as a proof of concept is quite common in the research community. In our literature survey, we found multiple works on prototyping AAL systems. A common approach found in several articles [65, 87, 31] was to utilize readily available boards such as Arduino-UNO/Raspberry-Pi, and smartphone applications for prototyping AAL systems. For instance, Hamim et al. [65] developed a prototype of IoT based remote health monitoring system for patients. The system consisted of a pulse, a temperature, and a skin response sensor which were combined into a single system using Arduino-UNO and Raspberry Pi. The data captured by the sensors was transferred to the cloud via Raspberry Pi and later accessed using an android based smartphone application. Apart from this, a prototype using RFID tags and Electronic Product Codes (EPC) [88], smart and connected home health monitoring system prototype called SilverLink [39], and a prototype for an indoor positioning system for elderly patients [151] were also proposed.

Standard Platform Related Frameworks. Some AAL systems use standard platforms such as, universAAL [66], ECHONET [99], and UPnP [34] and several works focused on solving existing issues related to these platforms. Lim et al. [91] presented a framework that works as a bridge between the universAAL and the ECHONET standard in the smart home environment and tries to eliminate interoperability issues of the standards. Similarly, a functional testing framework for smart home platforms has been introduced by Brink et al. [34] to assess the suitability of two AAL platforms namely universAAL and UPnP. The result obtain by the authors show that 4 out of 5 smart home applications in the AAL scenarios require a platform extension to work on the existing AAL platforms.

Requirements for AAL. AAL has some special requirements in comparison to standard IoT-based smart home systems. Thus, identifying the requirements and the existing problems in the domain is important. The articles focused on finding requirements in different aspects of AAL including costs, scalability, security, and Quality of Service (QoS) [50], secure and reliable health monitoring [115], context modeling [157], and service platform in the home, outside the home, and beyond [26]. Petrakis et al. [115] reviewed the key challenges for secure and reliable health monitoring based on their experience and learned lessons through applying IoT and cloud technologies for real-time data collection using health sensors as well as wide and short-range wireless protocols. The authors concluded that holistic approaches for seamlessly integrating recent advanced IoT and cloud technology protocols were missing and presented a service-oriented architecture iTaaS which they claim to be a contribution towards fulfilling the gap. Wojciechowski [157], in his work, first identified the requirements of context modeling (e.g. context adaptability, situation-aware service discovery, adaptability to available resources, etc.) in AAL from the end-user perspective and based on that introduced a three-layer context model that aims to satisfy the identified requirements.

In addition to AAL requirements, the user requirements of the system can also vary depending on the needs of each user. Thus, tailoring the system based on personalized user requirements becomes necessary. Among two articles found on this aspect, [58] focused on defining self-adaptive AAL service capable of automated dynamic reconfiguration of smart home infrastructure according to the user requirements and [149] proposed a visual end-user programming framework enabling custom automation for personalized requirements of AAL both inside and outside of the smart home environment supporting the everyday activities of the elderly.

Other Frameworks. Besides the frameworks discussed previously, we also found articles proposing frameworks related to decision support [165, 164], service oriented frameworks [156, 131, 105], hybrid AAL framework [67], threshold-based framework [134], and framework for assessing wellness [141].

Zhang et al. in [165] proposed a decision-making framework for an intervention mechanism supporting multi-inhabitants in a smart assisted living environment. The same authors in [164], proposed a decision support system for patients with Alzheimer's disease in a smart home for assisting them to complete activities of daily living (ADL). Besides, a Cloud-IoT-based sensing service scenario for health monitoring which is intended to facilitate sensing as a service for health monitoring and improve the overall service quality and accessibility has been proposed by Neagu et al. [105].

3.2 Sensors, Actuators and UI

Summary. *The interaction with the system and its components is crucial for AAL systems as it is intended for the elderly with special needs. Among several components of health monitoring or*

AAL systems, sensors, actuators, and user interfaces are the components that directly interact with the patients or the elderly in the environment. The success of such systems is highly dependent on these components. In our survey, we found several research works focusing on different aspects of sensors, actuators, and user interfaces in the domain of AAL. In terms of sensors, we found that the majority of the works focused on reducing the cost of sensors and improving the sensing quality in the context of AAL. Besides this, integrating robots in AAL and developing intuitive user interfaces were also popular research themes in this category.

Integration of Robots in AAL. The advancement in the field of artificial intelligence and machine learning has made it practically feasible to integrate robots into our daily life and make our life easier. In AAL environments socially assistive robots can play a vital role in facilitating the independent living of the elderly. Thus, multiple research works focused on different aspects of integrating socially assistive robots in the AAL environment. For instance, Bui and Chong [35] presented a novel approach to integrate human and socially assistive robots in universAAL and ECHONET standard-based AAL smart home environment through a multi-modal user interface. Based on a case study, the authors also showed that their proposed interaction interface enabled the robot to connect to the iHouse network and serve the users according to their request. Apart from this, [77] introduced a socially assistive robotic solution SARA for AAL and the challenges faced during the development process and [23] discussed the design principles and high-level architecture of the Florence platform which aims to provide loose coupling between the sensors/actuators and services of socially assistive robots to meet the dynamic requirements of the smart home environment.

Cost Reduction. AAL systems require many different sensors and devices to monitor the health and well-being of the elderly, however, these devices can be expensive. To make AAL systems affordable for everyone, reducing the cost of the hardware becomes necessary. Thus, the cost reduction of AAL systems is an active research topic in the domain. The works found in the survey on this aspect focused on low-cost sensor-based nocturia detection [143], low cost and energy-efficient home sensing Internet gateway based on Raspberry Pi [60], and low cost and rapidly deployable location-sensing [78]. For instance, Taramasco et al. [143] introduced low-cost sensor-based nocturia detection and also a novel fall detection mechanism for smart home-based AAL environment. Their experimental results showed that the work can be implemented in AAL scenarios as smart home devices and it is competitive compared to other similar tools.

User Interface. The user interface is one of the most challenging aspects of AAL systems since the majority of the end-users are either patients or elderly people. Hence, it needs to be simple and intuitive. The articles found in our survey on this topic worked on different issues, namely exploring the possibility of conveying activity information using ambient lighting [42], voice interaction-based smart personal assistant [36], investigation of Eclipse Smart Home (ESH) and Universal Remote Console (URC) platforms that aim to deal with user interface requirements of AAL systems [137], and usage of Avatars as components of the graphical user interface (GUI) for AAL [100]. Davis et al. [42] explored the features of ambient lighting to convey activity information to older adults from the perspective of caregivers in the AAL environment. In addition, the authors also assessed the implications of activity awareness through lighting on the cognitive performance, mode, and social connectivity of older adults. Morandell et al. [100] studied the usage of Avatars as components of the graphical user interface (GUI) for AAL environments which showed such GUIs are liked by the elderly with or without cognitive impairment more than traditional systems.

Sensing Quality. To improve the sensing quality of AAL systems, [142] proposed a smart non-invasive fluid loss measurement system, [120] developed an application with better architecture for monitoring patients in the hospital, and [37] proposed a sensing algorithm based on a single IMU for sensing basic events with better accuracy. Similarly, [158] proposed a data-driven storytelling system for transforming raw sensor data collected in IoT based AAL environment into a compelling story and conveying the elderly's condition to their loved ones in a more emotionally arousing and high persuasive manner.

3.3 Network Communications

Summary. *AAL systems are developed for remote health monitoring of the elderly which sometimes can lead to life-threatening critical situations. Thus, such systems require certain performance guarantees especially in the case of communicating the health data to the caregivers, hospitals, or family members of the patient. In our survey, we found multiple works focusing on communication performance in the context of AAL. Furthermore, these systems are built using sensors and devices from different vendors which work using heterogeneous communication technologies such as Wi-Fi, Bluetooth, or ZigBee. We found multiple works addressing the concerns of interoperability, interference, and coexistence issues caused by these different technologies.*

Performance Improvements. Sobral et al. [138] proposed a new routing metric specifically designed to fulfill the performance requirements concerning link quality and residual node energy of AAL-IoT applications. Using simulation, the authors showed that the proposed routing metric can meet the AAL requirements by increasing network performance. Khoi et al. [80] first identified the key network requirements in terms of real-time event update, bandwidth, and data generation of IoT based health monitoring systems and then proposed a new network architecture called IReHMO which aims to reduce the generated data volume and fulfill the bandwidth requirements of such systems.

Interoperability. Yacchirema et al. [159] proposed a prototype system for AAL called AAL-IoTSys to enable the interoperability between several heterogeneous devices communicating over heterogeneous protocols and technologies such as WiFi, ZigBee, Bluetooth, IEEE 802.15.4, 6LowPAN, etc. The system consists of a smart IoT gateway that facilitates interoperability by creating a Wireless Sensor Network (WSN). Additionally, [64] proposed an Information-Centric Networking (ICN) based IoT architecture for AAL to improve the communication performance of heterogeneous devices and services interacting in an IoT-AAL environment and [112] proposed an IPv6 and WSN based complete hardware and software solution which aims to solve the interoperability issues among traditional smart home and specially designed AAL systems.

Interference. Marinčić et al. [96] et al. investigated the problems of coexistence of technologies such as Wi-Fi, Bluetooth, BLE, and ZigBee in an AAL environment and based on that proposed the idea of cognitive radio as the solution of interference problem caused by the coexistence of such technologies. Ghayvat et al. [57] investigated the interference issues of ZigBee-based AAL systems. The study revealed that the reliability of such networks primarily depends on the distance, the deployment environment, and the position of sensor nodes.

Others. Cunha [41] presented an ambient lighting system called AmbLEDs which aims to replace invasive sensors and provide a novel interface for Visible Light Communication (VLC) for the AAL environment. Konstantinidis et al. [83] presented a Controller Application Communication (CAC) framework which aims to enable application-independent transmission of the controller (e.g. Wii family, Microsoft Kinect, Neurosky Mindwave, etc.) data to various software components designed for AAL.

3.4 Data Processing

Summary. *The sensors deployed in the AAL environment collect health and environment-related data of the elderly and send it to a cloud endpoint via the gateway for further processing. To detect health-related anomalies in real-time and notify the responsible stakeholders, efficient data processing techniques are required. In our survey, multiple research works focused on different aspects of data processing and proposed new or improved techniques for activity recognition, forecasting health conditions, fall, and stroke prediction, etc. in the context of AAL.*

Activity Recognition. Recognizing activity by processing the collected data in the AAL environment has been an active research topic in the domain. Several works ([110, 68, 128, 122]) explored the use of machine learning algorithms to recognize activities of the patients in the smart home-based AAL environment. Oniga and Sütő [110] presented a human activity monitoring and recognition system based on a neural network that aims to recognize the body and the arm postures and simple activities such as standing, sitting, walking, and running of the patients in smart home-based AAL environment. Some works focused on specific sensors such as single heart rate sensor and smartphone inertial accelerometer [102], wearable sensors [28] with machine learning techniques to improve the accuracy of detecting daily activities of the users in AAL scenarios.

Besides this, markov logic ([55, 47]), image ([121], audio ([148]), ontology ([22]), and conflict resolution ([130]) based approaches are also used for detecting activity and improving the accuracy activity recognition in AAL. For instance, Bianchi et al [28] proposed a human activity recognition system based on a wearable sensor and deep learning techniques to recognize the daily activities of a single user in AAL scenarios. The evaluation results revealed that with a relatively small training set the system is capable of classifying data coming from nine different activities with 97% accuracy. Vacher et al. [148] identified the challenges of audio recognition for activity monitoring and distress situation identification in an AAL environment by experimenting in a realistic AAL setting. According to the findings in the paper, for audio recognition, the main challenge is noise or environment perturbation, and for activity recognition, it is uncontrolled recording conditions and mixing of events.

Forecasting Health Conditions. Detecting health anomalies at an early stage can help to better treat the problem, and in turn, can save lives. In the AAL environment patients are continuously monitored and the data collected during the monitoring process can be used to forecast health conditions. The research works found in the survey used different approaches such as correlating lifestyle and health status [56], new profile generation approach [147], machine learning-based approach [95, 18], human behavior modeling approach [21], and noninvasive spatio-temporal abnormal behavior detection approach [85] to forecast health conditions. For example, Koutli et al. [85] proposed a noninvasive spatio-temporal abnormal behavior detection approach by combining classification and regression-based approaches. The approach elaborates data from IoT sensors and creates behavioral profiles of the inhabitants and based on that detects deviations for abnormal behaviors. The evaluation results revealed that the proposed approach can detect abnormalities and provide insightful information to caregivers. Azefack et al. [21] proposed a human behavior modeling framework in smart homes. The proposed model utilizes high-level activities-labeled data, patterns, and relationships between activities to model user behavior. The authors showed that the activities-labeled data collected in a smart home environment are enough for building a virtual representation of the inhabitants' lifestyles.

Some works also investigated the accuracy and efficiency of different techniques to forecast health conditions. For instance, Jouini et al. [75] investigated the accuracy of Grey

Model GM(1,1) as a forecasting method to predict the states of elderly in an AAL environment and found that it is more efficient and accurate than other similar techniques. Similarly, Disi et al. [44] explored the efficiency of real-time ECG signal reconstruction on heterogeneous multicore IoT-gateway and also investigated the effects of signal dimensions and utilization of resources on reconstruction quality, execution time, and energy consumption.

3.5 Survey/Review

Summary. *Among the literature found during the survey, several works conducted surveys, reviews, and studies regarding various aspects of AAL. The papers mostly focused on investigating the market potential, the requirements and challenges, the impact, and also the applications of different technologies in the context of AAL.There are arguments both in-favour of and against including survey and review articles in a systematic literature review. In our case, we decided to include the surveys and reviews since we are interested in AAL research on a meta level and including them aligns with our research goal. It is worth noting that, in this work, we refer to works purely based on literature as surveys and works conducted based on elements such as interviews, field study, user studies, etc. as reviews. In our literature search, we found three survey articles ([49], [38], [111]) that are related to our work, we discuss the articles in Section 7.*

Future Technological Requirements of AAL. Wan et al. [153] presented an overview of IoT-based AAL systems and applications intended specifically for the healthcare domain and also identified the challenges and future research directions of the domain. According to the authors, managing the high volume of data generated by the IoT environment, lack of robustness and reliability in the systems due to their dynamic nature, and human behavior recognition are some of the key challenges and future research directions in the domain. Pérez-Castrejón and Andrés-Gutiérrez [114], in their study, investigated the need and the ways of developing AAL services that can be integrated and are compatible with the mainstream technologies of the digital home instead of building such services as individual technical solutions. According to the authors, entertainment technologies and standards available in a digital home can be utilized for providing AAL services and building a smart home ecosystem. Hoof et al. [150] studied the design requirements and expectations of end-users, their families, and caregivers regarding AAL technologies with respect to the healthcare industry in the Netherlands. The results show that there are concerns among end-users regarding motivation for use of technology, lack of user involvement during the design phase, privacy, and ethics-related issues.

Integration of Technologies for AAL. The integration of Artificial Intelligence (AI) technologies can solve a lot of existing problems in the AAL domain. Several research works studied different aspects of integrating AI technologies in AAL. For example, Begg and Hassan [25] studied the applications of artificial neural networks in building a smart home and assisted living environment and also discussed how neural networks can be used to solve existing issues of the domain. Similarly, [73] studied the opportunities and challenges of artificial intelligence, machine learning, data mining, and other intelligent agent technologies and [82] studied the integration of heterogeneous new technologies for future healthcare with the focus on IoT and AI-related computing solutions.

Prospective and Impact Study of AAL. Savage et al. [129], in their study, investigated the market potential and the socio-technical challenges of implementing AAL services specifically focusing on the healthcare industry of Canada. According to the authors, fragmentation of the market with 100 different health authorities serving patients all over Canada is one of the main barriers to introducing new healthcare technologies such as AAL. Leitner et al. [89], in their study, explored the feasibility of AAL deployment in rural regions by performing a longitudinal field study with 20 participating households. According to their findings, the participants were positive towards the usefulness of AAL technology and also suggested some enhancements to the system. Furthermore, Beringer et al. [27] conducted a study on the impact of AAL systems on the life of the end-users using an alternate research approach which consisted of semi-structured interviews with 12 end-users of the system. Their results show that the participants are mostly concerned about privacy and interference with current lifestyle whereas happy regarding the independence and the security provided by the AAL systems.

3.6 Security

Summary. *Security and privacy are two of the main challenges for any technological solution and AAL is no different. AAL systems deal with individuals' inherently privacy-sensitive health data, thus ensuring security and privacy of the systems becomes even more crucial. Even though the domain possesses some unique challenges in terms of privacy and security, in our literature survey we found very few articles dealing with them. The papers found under this category mostly focus on security aspects such as authentication, access control, secure data transfer, etc. of AAL.*

Doukas et al. [48] proposed an AAL system based on Gateways that aggregate sensor data and uses digital certificates and PKI to resolve security issues of the system. The IoT gateway in the proposed system aggregates the health sensor data and uses PKI and digital certificates to securely transfer it to the interested parties.

Porambage et al. [119] proposed a novel proxy-based lightweight authentication and key establishment protocol specifically designed to secure sensitive data generated by resource-constrained devices in IoT-enabled AAL systems. The proxy-based approach is used for facilitating the delegation of computationally heavy operations to more powerful devices available nearby in the AAL environment.

Massacci et al. [98] presented an access control model for AAL in smart homes which is based on the notion of organizational model and implements no purpose, no data scheme for the access control. The organizational model is responsible for mapping goal-to-role relationships specifying which actor is responsible for which goals. The proposed system constrains the access control using a system goal model which describes the organizational model and specifies the different goals associated with a role and different objects and permissions needed for the corresponding goals. A permission is only granted to a user if a predefined security policy allows it and the user is going to fulfill a certain purpose.

Khayat et al. [79] first studied the security and privacy concerns of existing health monitoring systems and concluded that all security components (confidentiality, integrity, and availability) need to be addressed to ensure security and privacy of such systems. To address this, the authors then proposed a reference architecture based on Software Defined Networking (SDN) for ensuring security, privacy, and reliable service delivery of health monitoring systems. The proposed security integration framework enables the benefits of functional and secure applications and services provided by SDN and removes the dependency on vendors and software for security needs. The implementation and performance evaluation of the proposed work were mentioned as future work.

Koutli et al. [86] first analyzed the security requirements and challenges of e-Health IoT applications and then proposed a complete architecture to address the issues. According to the authors, to consider an IoT application secure, security features such as authentication, authorization, confidentiality, integrity, availability, privacy, and trust management need to be addressed. Apart from general IoT security requirements, health applications have additional privacy and ethical concerns such as consent and privacy by design regulated by GDPR in Europe which makes the security of such applications more demanding. To address this, the authors presented an e-health architecture that integrates two e-health applications AAL and mHealth into the VICINITY framework and aims to tackle IoT security and privacy concerns and offer robust solutions. The authors also developed mechanisms for dealing with GDPR requirements in the context of consent, auditing, and the right to be forgotten. The patients need to provide consent using a mobile application for at least one doctor and one guardian who can access their data and the architecture consists of a consent control service that is responsible for controlling who can access what data. The consent can be easily revoked by the patient at any time using the mobile application. The work lacks an evaluation of the proposed approach.

3.7 Business Model for AAL

Summary. *AAL systems involve many stakeholders and in any such scenario a business model is necessary to fairly allocate any revenues or other factors relevant for monetary profit. In our survey, with its basis in computer-science research, we found only a very limited set of papers addressing this issue.*

Grossmann et al. [61] and Bleja et al. [32] presented a collaborative business model for AAL that provides fair allocation of revenues, cost savings, and a data fair share concept. The authors extended the standard canvas business model to a superordinate collaborative system business model for integrating multiple service companies and external stakeholders into the model. The basis of the model is that the incoming revenues including external financial contributions must have a fair distribution using methods of cooperative game theory among collaborating business partners. The initial idea of the business model was first presented in paper [61] and the concrete model with example scenarios was presented later in paper [32].

4 Survey on Commercial Systems

Besides the academic literature, we also conducted a survey on commercially available ambient assisted living or remote health monitoring systems to have insights into the current market situation. The main motivation behind this survey is to find out whether the commercial systems conform to the findings of the literature or not. Moreover, the commercial systems have to comply with certain privacy and security regulations such as the GDPR in the EU to be sold in the market. So, we also wanted to see whether these systems take any additional privacy measures to comply with the regulations. We included 11 commercial AAL systems available in different countries around the world. Table 2 provides an overview of the surveyed commercial systems. Most of the commercial systems consist of multiple sensing devices with different sensors such as fall detection, motion sensor, door sensor, location sensor, step counter, blood pressure, heart rate, camera, etc. The data collected by these sensing devices are communicated to a cloud server or portal via a gateway or a smartphone. The cloud server or portal enables access to the sensed data for different stakeholders of the system such as caregivers, hospitals, and family members. For the communication between the gateway/smartphone and the sensing devices, short-range technologies such as Bluetooth, Wi-Fi, and RFID are most common. For the communication between the gateway/smartphone and the cloud server, Internet enabling technologies such as cellular, wired telephony or broadband, and Wi-Fi are widely used.

Name	Country	Devices	Communication	Sensed Info	Data Sent to	Security and Privacy
Smart Care (Care@ Home Platform) [11]	Israel, Australia, Spain	Control Panel, Emergency Pendant, Voice Panic Detector, Door Sensor, Camera, Motion Detector, Flood Detector, Smoke Detector	Cellular 2G/3G/4G (HSPA+), Proprietary bi-directional radio protocol (RFID)	Fall Detection, Door Open/Close, Image & Motion, Water Level, Smoke, Voice	Gateway, Cloud	Nothing mentioned in website/brochure regarding security and privacy considerations
GreatCall [4]	USA	Lively Mobile Medical Alert, Lively Wearable	Cellular 2G/3G/4G (HSPA+), Bluetooth	Location, Fall Detection, Step Counter	Web Server, Mobile	Nothing mentioned in website/brochure regarding security and privacy considerations
Gociety Solutions [7]	Netherlands (EU)	Go Live Clip	Bluetooth	Step Counter, Fall Detection	Web Server, Mobile	Nothing mentioned in website/brochure regarding security and privacy considerations
Care Link Advantage [3]	Canada	Control Panel, Motion Sensor, Bed Sensor, Door Sensor	Wired Telephony, Wireless Communication with Control Panel	Motion, Bed Activity, Door Open/Close	Gateway, Web Server	Nothing mentioned in website/brochure regarding security and privacy considerations
Grand Care [8]	USA, UK, Canada, Bermuda, New Zealand	Touch Screen Panel, Motion Sensor, Door Sensor, Blood Pressure, Weight Scale, Glucometer, Ear Thermometer, Oximeter	Wireless/Wired Communication with Care portal, Bluetooth Communication with Touch Panel	Motion, Weight Door Open/Close, Blood Pressure, Blood Sugar, Temperature, Blood Hemoglobin	Web Server	Uses VPN and Encryption for securing the data and the communication.
Zanthion [13]	USA	Wearable Sensor, Android TV Player & Gateway	Wi-Fi	Motion, Blood Pressure, Heart Rate, Acceleration	Gateway, Web Server	Nothing mentioned in website/brochure regarding security and privacy considerations
Independa [9]	USA	TV	Wired/Wireless Communication	Video, Image	Gateway, Web Server	Nothing mentioned in website/brochure regarding security and privacy considerations
Coala Life [5]	Sweden	Heart Monitor	Bluetooth	Heart Values	Cloud	Nothing mentioned in website/brochure regarding security and privacy considerations
Philips Lifeline [10]	USA, Canada	Wearable Sensor	Landline/Cellular Communication	Fall Detection	Gateway, Cloud	Nothing mentioned in website/brochure regarding security and privacy considerations
Blodtrycks-doktorn [2]	Sweden	Blood Pressure Monitor	Wi-Fi/Cellular Communication with Smartphone	Blood Pressure	Smartphone, Cloud	Nothing mentioned in website/brochure regarding security and privacy considerations
Canary Care [6]	UK	Wireless Hub, Motion Sensor, Door Sensor, Temperature Sensor	Cellular Communication	Motion, Light, Temperature, Door Open/Close	Gateway, Cloud	Mentions that it provides complete privacy by not using any camera or mics

Table 2: Commercially Available Ambient Assisted Living Systems

It is evident from the survey that these devices collect a lot of data of the user and their environment which are privacy-sensitive. However, most of these systems do not disclose any information regarding how they protect the privacy of the user in the product information found in their respective websites and/or brochures. The commercial systems have to take necessary measures to protect privacy-sensitive data due to legal requirements such as the GDPR; however, we found that the information regarding that is not made easily accessible to the users. Among the 11 systems under review, we found only one system that discusses its security measures. Grand Care [8] system uses VPN and encryption for securing the data and the communication of the system. Nonetheless, the information regarding data collection, storage, privacy preservation, and security measures are not clearly stated by any of the systems under survey. The vendors may have the information in the respective license agreements to fulfill the legal obligations, it should also be highlighted in the product promotion and advertisements. The users must have easy access to information such as what data these systems collect, where the data is stored, and how it is protected.

We do not find any such information by surveying the websites and/or brochures of the systems.

5 Findings

In Section 2.2, we constructed several research questions to understand the current state-of-the-art of AAL systems. In this section, we discuss the findings of the research questions.

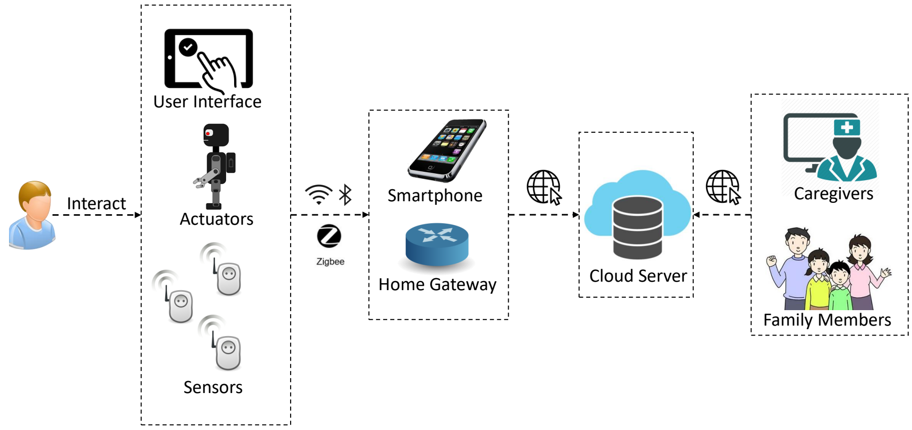

Figure 2: General Architecture of Smart Home Health Monitoring Systems (RQ1.1)

5.1 RQ1 Architecture of the frameworks or systems

The majority of the articles proposed frameworks or prototypes for AAL by integrating different technologies. Figure 2 shows the general architecture of smart-home based health monitoring systems found in most articles and commercial systems **(RQ1.1)**. The smart home environment consists of sensors and actuators. The sensors can be either invasive or non-invasive and are deployed in the smart home environment or body-worn by the patient. The patient/elderly interacts with the system with some user interface. The sensors collect the patient's health and surrounding environment-related data and send it to a centralized entity such as a home gateway or a smartphone. For the communication between the sensors and gateway/smartphone, wireless technologies such as Wi-Fi, Bluetooth, and ZigBee are commonly used. The gateway/smartphone aggregates the data and sends it to a remote server/cloud over the internet. The cloud then enables data processing and access to these data to different interested parties (e.g. caregivers, doctors, etc.). The survey reveals that smart home-based remote health monitoring systems are mostly centralized in terms of architecture **(RQ1.2)**. Commonly, a home gateway or smartphone works as the centralized entity which aggregates the data from the sensors and other components and relays it to a cloud server for further processing. The commercial systems also show similar characteristics as in the literature regarding the architecture of the systems.

Interpretation and impact on privacy: The commonality of the basic architecture for both academic and commercial systems may result in standards and simplify the landscape for privacy research. While nearly all systems use gateways, they are often separate for each system, though some consolidation has started. If that trend continues, the potential for local data protection could increase, yet isolating services from each other is necessary. This is in analogy to what is already an at least partially addressed issue in the cloud and on mobile phones, where clients and apps must not interfere with each other or obtain information in an unauthorized way, e.g., by side-channel attacks.

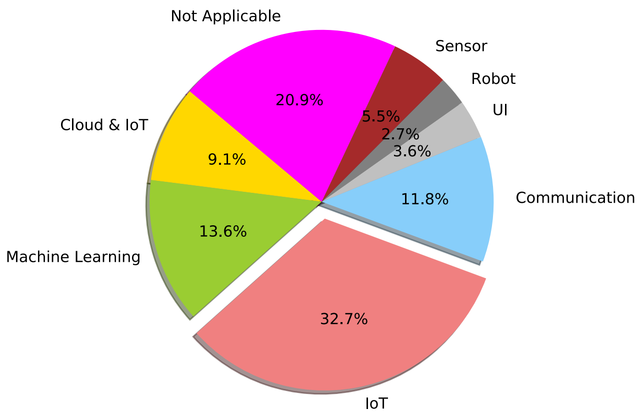

Figure 3: Technology Focus of the Articles (RQ2.1)

5.2 RQ2 Technologies used to develop the AAL systems

To gain more insights, we also looked into the technology focus of the research articles **(RQ2.1)**. This allows us to evaluate the systems based on the known security and privacy issues of the particular driving technology. Figure 3 depicts the findings of the research question **RQ2.1**. As shown in the figure, IoT is the most dominant technology for AAL systems, the focus of about a third of the articles. Since AAL is a smart-home based technology which in turn is an application of IoT, the dominance of IoT is evident. Besides IoT, several articles focused on communication (about one in 8 articles) and machine learning (about one in 7 articles) related technologies. In terms of communication technology, the articles mostly focus on tailor-made home gateways for AAL and interoperability between different wireless technologies, whereas machine learning techniques are mostly used for activity recognition in the AAL environment. Sensors, cloud and IoT, UI, and robots are some of the other technology focus of the articles under review. For some of the articles, this research question was not applicable as they were either a survey, study, or other similar research work that does not explicitly focus on any particular technology and they are shown as Not Applicable in the figure.

Interpretation and impact on privacy: IoT and cloud computing are the technology focus of about half of the papers in our survey where that was applicable. Machine learning is on the rise and if included raises the coverage to more than two-thirds of the papers. Contributing privacy research to these areas thus potentially has a large impact on research in AAL overall.

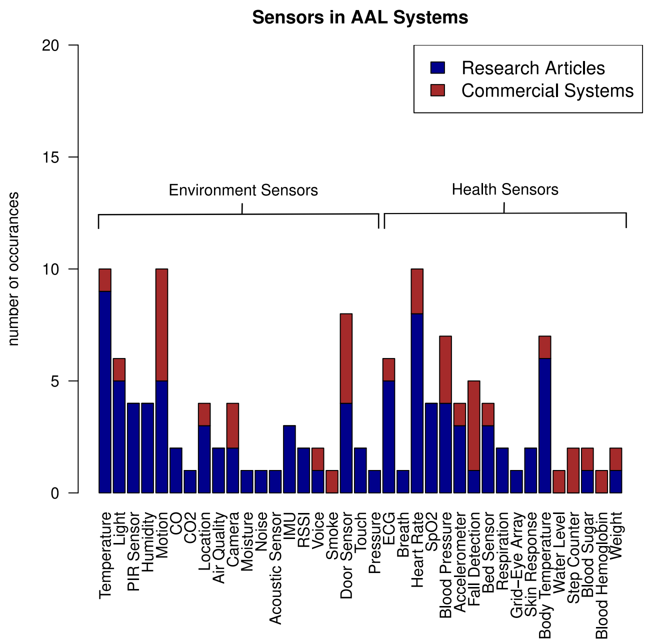

Figure 4: Data Collected by AAL Systems (RQ3.1)

5.3 RQ3 Data handling of the AAL systems

Since AAL systems deal with privacy-sensitive health data, we looked into the data handling mechanism of these systems. We focused on two specific aspects of data which are data collection **(RQ3.1)** and data storage **(RQ3.2)**. The key enabling component for data collection is sensors. AAL systems typically deploy multiple sensors to collect data of the elderly or the patient. Thus, we investigated what different sensors are used by these systems to collect the data. Figure 4 provides an overview of the health and environment sensors used by AAL systems both in the literature and by commercial systems **(RQ3.1)**. Among environment sensors, temperature, light, motion, and door sensor are some of the most common sensors whereas in terms health ECG, heart rate, blood pressure, fall detection, and body temperature sensors are widely used both by the commercial systems and in literature. By combining the data collected from multiple sensors, additional inferences such as presence at home including of other people, activity at any given time, etc., can be made and potentially misused. Thus, ensuring the security and privacy of the data is very important.

Similarly, we also investigated the data storage of AAL systems. Figure 5 provides an overview of data storage in AAL systems both in the literature and by commercial systems **(RQ3.2)**. As depicted in the figure, for local data collection, aggregation, and storage, a gateway or smartphones are typically used in AAL systems. However, for long term storage and processing of the collected data, cloud storage (n.b. here server/webserver are considered as cloud) is most popular among AAL systems. The AAL systems collect (and potentially aggregate) sensor data either in smart-home gateways or in smartphones locally, which in turn transfer the data to a cloud server for further processing and long-term storage. This seems to be the norm for data storage both in the literature and among commercial systems.

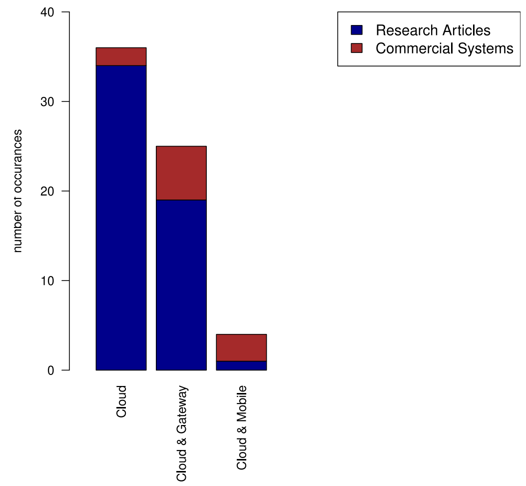

Figure 5: Data Storage in AAL Systems (RQ3.2)

Lastly, we also investigated the security and privacy considerations **(RQ3.3)** of the research articles. Figure 6 provides an overview of our findings **(RQ3.3)**. As depicted in the figure, even though AAL systems deal with privacy-sensitive data, most articles do not discuss any security or privacy aspects of AAL systems or have any security and privacy consideration in their proposed work. Among the articles under review, we found that around 67% articles does not have any security or privacy consideration. Around 14% of the articles mention security and privacy as a requirement, challenge, or future work. Similarly, we found that only 18% of the articles consider security and privacy aspects and provide solutions to ensure them, of these only 5 articles (4.5% of the total) focus on security or privacy.

Interpretation and impact on privacy: Data is collected by a large and diverse set of sensors, with input both from an individual person and their environment, potentially gathering information about other people in the home as well. In this work, we do not compare/correlate sensors and their privacy invasiveness, since it is not possible to predict which data can have what kind of privacy and security implications in a certain context. For instance, environmental data such as room temperature and humidity may not seem to be private information. However, such room climate data can detect the presence of a person in a room with 93.5% accuracy [101] which is a privacy-sensitive information. Moreover, combining the input from several such sensors can lead to inferences that are not available from analyzing sensor data individually, adding another privacy concern.

Storage and processing is mainly done in the cloud, which raises the question of how data is protected both in transit and at rest in the cloud. Again, local processing or data transformation for privacy preservation could be used for data minimization and risk reduction.

The scarcity of privacy or even security considerations in the papers shows that Privacy by Design has not become mainstream yet, and the development of function or performance is separated from security and privacy aspects which are presumably left to be added later by specialists.

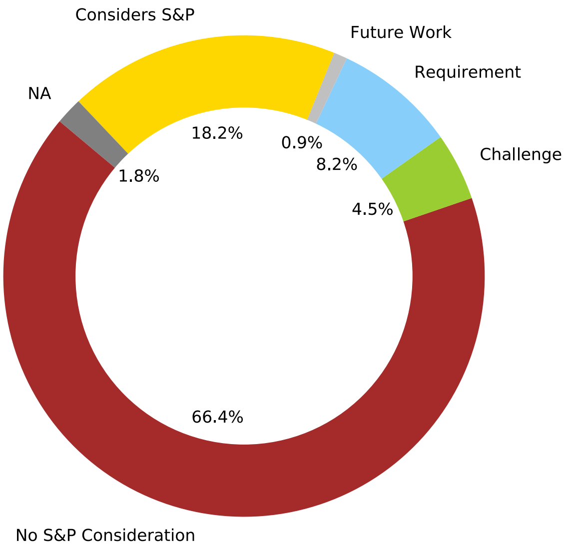

Figure 6: Security & Privacy Considerations of the Articles (RQ3.3)

5.4 Trends and Observations

To have a holistic view of how the research is progressing over the years in the AAL domain we looked at the trend of the papers included in our review. The figures are provided in Section C under the appendix. Figure 8 shows the trend of all the 110 papers under review. As shown in the figure, research on AAL started booming from the year 2015 onward and continued since then. This could be because around 2014-2015 the use of IoT devices also started increasing significantly. According to IoT Analytics Research, the number of active IoT devices almost doubled from 3.8 billion in 2015 to 7 billion in 2018 [93]. Moreover, the rapid growth of artificial intelligence and machine learning from 2017 onward further boosted the research on AAL during those years. For example, according to our research on IEEE and Web of Science (WoS), the number of papers on machine learning has almost tripled in the last five years.

We also looked at the research trend within each research theme category that we categorized in Section 3. Figure 9 in the appendix shows category wise research trend. It is important to point out here that for the categories it is difficult to analyze trends due to reasons such as not enough papers in some categories, no papers found in some years, nothing conclusive can be drawn, etc. Hence, we try to provide our observations based on the data we have. For the Framework category, we observe that from 2015 onward the number of papers started increasing which is similar to what we see in the case of the overall trend. However, in the case of years 2013 and 2014, it is not possible to conclude anything since in 2013 there were 5 articles which is a significant number whereas in 2014 the number was 0.

For Sensors, Actuators, & UI category, we observe that between the years 2016 to 2018 significant number of works have been done on the topic. However, in 2019, we did not find any work related to this topic. We think that the reason behind the trend between 2016 to 2018 can be the boom of IoT during that period as mentioned previously and for 2019 it can be that the research problems on the topic may have become saturated. For the Network Communication category, we observe the opposite trend where the number of articles started decreasing every year starting from 2015 until 2017 and then onward became zero. We think that since the most pressing problems of network communication of low-powered devices have already been solved, we see such a trend. For Data Processing, we see a significant increase from 2018 and onward which can be due to the advancement and increased usage of machine learning and artificial intelligence technologies around those years. Lastly, in the case of Survey and Security categories, we were unable to conclude anything due to the lack of papers under those categories.

6 AAL Security and Privacy Challenges

The primary goal of this systematic literature review and the survey on commercial AAL systems is to understand the state-of-the-art AAL systems and their security and privacy considerations and implications in order to identify the potential challenges and future research directions in the domain. However, according to our findings, both the literature and the commercial systems reveal very little information about the privacy and security aspects of the AAL systems. It is alarming that there is very little or no consideration regarding security and privacy, even though these systems deal with privacy-sensitive data. In this section, we try to identify the potential privacy and security challenges of AAL systems by combining the facts we learned from the review and by comparing AAL with other similar fields.

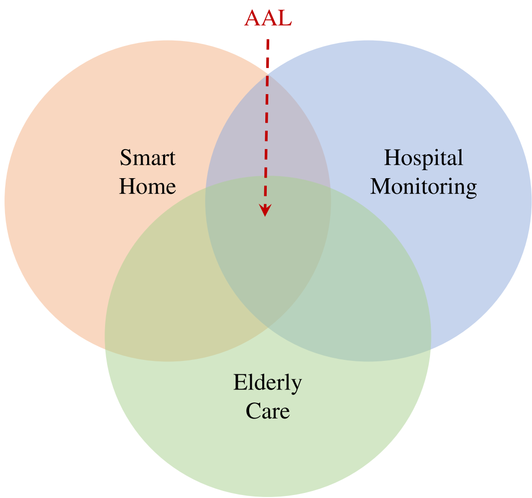

Figure 7: Fields Combined by AAL

AAL technology combines the concept of smart home, health monitoring in hospitals, and elderly care. Each of these fields possesses some unique challenges in terms of security and privacy. Thus, it is not unrealistic to assume that the existing privacy and security solutions and the upcoming future research works in these individual fields are sufficient to solve the problems of AAL systems. However, the assumption does not hold in reality. Even though AAL incorporates the concepts of several fields, it has some unique challenges in terms of privacy and security that are not present in other fields. For instance, typical smart home systems consist of sensors that usually only collect the user's environment-related data but not health-related data. Conversely, hospital monitoring systems do not collect the surrounding environment-related data of the patients. AAL systems, however, collect both health and environment-related data of their users, from which one can infer more information than from the individual data, adding to the privacy risk. Figure 7 shows the intersection of the fields that make up AAL technology, where unique challenges arise.

One of the key findings of our survey is the generic architecture of the AAL systems. Both literature and commercial AAL systems follow a similar architecture as shown in Fig 2. The architecture can be used as the basis for finding potential security and privacy issues of AAL systems. For this, we identify distinct parts of the architecture and regard them as intervention points. They are sensors and actuators, user interface, communication, home gateway, cloud server, and data access, and we discuss the security and privacy of AAL systems across them.

6.1 Sensor and actuators

Sensors and actuators are among the most essential elements of AAL systems. Sensors collect health and environmental data and actuators take necessary actions based on the processed data. The sensors and actuators are mostly low-powered devices which makes them easy targets for attackers. In most cases, security or privacy solutions are resource-intensive and can not be directly deployed on low-powered devices. The solutions that can run on such devices are not robust enough and easy to break. Thus, the attackers find it convenient to attack such devices. Securing low-powered IoT devices is a popular research topic and resource-efficient security solutions indented for such devices can also solve similar issues in the AAL domain.

For privacy, we need to ensure that the sensors are collecting only the necessary information and no extra information. The less the data is collected, the smaller the privacy risk. Data minimization is needed not just for what data and how much of it is collected, but also for storage and in terms of what data can be combined, leading to stringent requirements of isolation. Even a small and targeted data collection can lead to undesirable inferences, as has been shown for the case of smart metering. There, researchers were able to map patterns of energy consumption to specific types of appliances [51]. Knowing then, for example, when a stove was or was not used could even lead to inferences about a person's adherence to rules of a particular religion.

6.2 User Interface

One of the key difference between AAL systems and other smart home systems is that AAL systems are intended for elderly people to facilitate their independent living, which adds challenges to an already ubiquitous problem. Elderly people usually have not been interacting as much with newer technologies and may therefore lack technological skills and may have some cognitive limitations necessitating AAL assistance in the first place. Therefore, the technological solutions intended for them needs to be even more user-friendly, intuitive as well as secure.

Since the AAL system collects privacy-sensitive data of the elderly, it must provide an intuitive user interface for the elderly to easily control the privacy settings of the system. For instance, if a user wants to change the system's privacy settings and does not want to share particular data at any given time, they should be able to do it without much prior technological knowledge. Moreover, there need to be provisions for taking the consent of the user before collecting any data. This is currently lacking in AAL systems. The process of deploying an AAL system can vary from country to country due to different regulations and other factors. For instance, in some situations, the government or local administration may deploy AAL systems for an inhabitant whereas, in some others, hospitals or family members may deploy such a system. In such cases, the elderly may not be aware of or asked for consent to collect their personal data. However, according to the GDPR, when the legal ground for data collection is consent, the user needs to be clearly informed about what data are collected and why. Hence, how to take consent in an AAL environment is an important open research question, for trust and liability reasons.

6.3 Communication

In a typical AAL system, communication happens in two steps, first between sensors and the home gateway and second between the home gateway and the cloud server. The communication between the devices and the gateway typically happens using short-range communication technologies such as Bluetooth, Bluetooth Low Energy, and Zigbee, etc. The security measures used in these short-range technologies are usually not robust as they are used in resource-constrained devices. Securing the short-range communication technologies is an active research field and AAL does not pose any new challenge in the area, only increased importance. Since the data is very personal and can be critical for health, all three of the classic CIA properties, confidentiality, integrity, and availability, have more stringent requirements.

6.4 Home Gateway

The home gateway in an AAL system is the entity that consolidates or aggregates the data collected by the sensors and sends it to the cloud server. In terms of privacy, the gateway can play a vital role by sending only the necessary information to the cloud server instead of all information. This will require some local data processing on the gateway. The gateways are usually high-end devices with decent processing power and not limited by energy constraints. Thus, an open research question in terms of AAL is how to apply data minimization techniques on home gateways to identify, potentially transform (e.g., by using advanced cryptography such as homomorphic encryption), and send only the relevant information to the cloud server, for improved privacy. Currently, separate AAL systems mostly also have separate gateways. Some efforts of integrating gateways such that they can be used for several systems are underway and if this trend continues, standardization may follow, as well as techniques for isolation between different services in analogy to cloud servers and mobile phones hosting multiple clients or apps.

6.5 Cloud Server

The cloud server in AAL systems is the entity that stores the collected data and enables access to it for the different stakeholders. The cloud server also facilitates the data processing which helps the interested parties to gain key insights from it. For AAL, mostly the cloud infrastructure is provided by the vendors of the system. Thus, the cloud servers contain data from multiple customers of the vendor and secure storage of individual customer's data is necessary.

Vendors may want to analyze and use the collected data to improve the service or even share it with other interested parties (e.g., advertisement or pharmaceutical companies). However, as the data is privacy sensitive, to get benefit from the data is not straightforward.

Therefore, the key challenges for the cloud server in AAL are secure data storage, access control, and privacy-preserving data processing and disclosure.

6.6 Data Access

AAL systems involve multiple stakeholders such as the users themselves, their caregivers, hospitals, family members, and vendors who need to access the data collected by the system. To ensure secure access, a fine-grained access control mechanism is needed which enables only the necessary information to the authorized interested party. Furthermore, the data from AAL systems are of great potential value for medical research, which would require disclosure in a suitable way. To protect the privacy of individuals present in the data, techniques such as data sanitization, data anonymization, and differential privacy need to be applied before the data of multiple patients can be disclosed.

The data generated by AAL systems combine both health and environment-related data of individuals which makes it more privacy-sensitive than individual health or environment data. Moreover, to get benefit from such data and use it for medical research or to apply machine learning techniques for gaining more insights, the data needs to be highly accurate, especially if used as the basis of the individuals' healthcare decisions. However, privacy-enhancing technologies commonly apply noise to the data for preserving the privacy which reduces the utility of the data. Thus, a research challenge in terms of privacy for AAL is how to apply privacy-enhancing technologies on such data without hampering the utility provided by the data.

7 Comparison with the State of the Art

Our research work is closely related to health monitoring, smart home and IoT, and security and privacy. We thus compare our findings with the works under these three major categories.

Health monitoring. Recently, several research work focused on investigating the state-of-the-art health monitoring systems. Duarte et al. [49] conducted a tertiary study to investigate the state-of-the-art AAL platforms, their development patterns, and the key challenges in the domain. Based on their study, the authors concluded that the lack of AAL-focused reference architecture and problems regarding usability and data security are some of the main challenges in the domain. The authors also mentioned that it was difficult to obtain more accurate data since the studies they found were mostly not AAL focused. In contrast, we found the overall architecture we distilled from the papers not only to be the most common but quite uniformly adopted, and we did find a large number of AAL-focused papers with our queries. Their findings on security and usability are borne out by ours. Chiuchisan et al. [38] conducted a survey on IoT and its applications in the e-health domain along with a case study using the K53 Tower System e-health platform. According to the authors, two fundamental and very important aspects of e-health systems monitoring people at risk are prevention and effective intervention. To address this, the authors also proposed a novel e-health solution which specifically focuses on the two aforementioned aspects. Pal et al. [111] conducted a systematic literature review on smart homes and smart environments intended for assistive living for the elderly which investigates the influence of such systems or environment on the living quality of the elderly involved. Their findings show that even though the elderly people are positive towards smart home-based

AAL systems for independent living, they are seriously concerned about the privacy and security provided by such systems as well as the fear of social isolation due to technology dependency. Our findings show that these concerns are still to be addressed. (Note that the above-mentioned papers were among those we found in our systematic literature review; the rest are related in other ways.)

Majumder et al. [94] conducted a review on state-of-the-art research and development in smart home-based health monitoring technologies. Based on the review, the authors concluded that a full-fledged smart home is still far from reality and more research and development is required for developing a fully-functional smart home. The authors also emphasized the need to ensure reliability, privacy and data security, low setup and maintenance cost, etc. of such systems. Though we did find a number of proposed frameworks, which should go toward such a fully-functional smart home, the needed properties they identified are not provided, let alone integrated. The authors' view that adoption of AI technology would help build fully automated and self sustainable solutions is matched by the increasing number of AI papers we found.

All of these works primarily investigate the state-of-the-art health monitoring systems which matches one of our research goals. However, security and privacy concerns and considerations of health monitoring devices are not part of these works.

Smart Home and IoT. With the globalization of the Internet, technologies such as IoT and smart homes are becoming popular. The popularity of these technologies is, in turn, inducing numerous research works in the domain. Though these works do not focus on AAL or privacy, they are still relevant in the broader context of AAL. Gaikwad et al. [54] conducted a survey on smart home systems using IoT and identified the problems and challenges of such systems. According to the authors, managing increasing applications of IoT, server-side security, and uninterrupted connectivity are some of the key challenges in the domain. Similarly, Stojkoska and Trivodaliev [140] reviewed the state-of-the-art research on IoT based smart home and smart grid solutions and identified the future research challenges of the domain. The authors argue that big data, networking, interoperability, and security and privacy are some of the main practical issues in the domain. Furthermore, Shah and Yaqoob [132] conducted a survey and identified the applications (e.g. smart cities, smart manufacturing, health, automotive, etc.) and challenges (e.g. availability, reliability, scalability, interoperability, security and privacy, etc.) of IoT technologies. Singh et al. [135] also conducted a similar survey and identified the challenges (i.e. communication challenges and data fusion challenges) and presented a future vision (i.e. things-oriented vision, Internet-oriented vision, and semantic-oriented vision) of IoT technologies. In relation to these works, we found that, at least in the context of our literature review, the research on availability, reliability, scalability, and connectivity concerns as well as networking more broadly has lessened as some of the challenges have been overcome. Interoperability concerns are mostly being evaded by either gateways capable of handling different technologies or separate gateways for each system, and big data and data fusion is more and more handled by machine-learning approaches.

Security and Privacy. Due to the advancement in different technologies, our day-to-day activities have shifted from physical to the virtual domain. Even though these technologies provide a lot of benefits and make our life easier, they also introduce new problems and challenges. Security and privacy of cyber-physical systems is one such challenge that has drawn a lot of attention from the research community in recent years. Rushanan et al. [127] conducted a survey on security and privacy of implantable medical devices (IMDs) and health-related body area networks (BANs). The main concerns raised were the security of telemetry interfaces of sensors, possible electro-magnetic interference attacks on the sensor interface and eavesdropping on physiological signals, and reproducibility challenges due to lack of access to devices. We did not find these concerns represented in the wider AAL context, although BANs and IMDs can be part of AAL.

Furthermore, Alrawi et al. [16] identified attack techniques, mitigations, and stakeholders of home-based IoT deployments by grouping papers according to layers (devices, mobile applications, cloud end-point, and communication). In addition, the authors evaluated 45 devices and found several security issues, such as misconfiguration, vulnerable services, and lack of encryption. Though their focus on security and approach differ from ours, they also compared the literature to existing devices and found much of the same issues in both, which matches our experience in this work.

Batalla et al. [24] presented current security approaches in the smart home environment by dividing them into layers (e.g. network, application, perceptual, etc.). Then the authors identified threats in different layers and their countermeasures (i.e. confidentiality/privacy, integrity, authenticity, non-repudiation, availability, and authorization) and presented some good security practices (i.e. security audits, using strong standardized cryptography methods, user data protection, etc.) to be followed. The authors also discussed open research issues where they argue about the introduction of external actors for the management of smart home systems that will introduce security in all layers and ensure the privacy of data and tried to convince that the network operators (e.g. multimedia or internet providers) are best suited for the job. According to them, for realizing such a system managed by external actors, two key elements are necessary: a Multi-Functional Home Gateway (MFHG) and a HAN Management System (HMS). Most of the identified threats, countermeasures, recommended good security practices, and the argument of a secure-centralized home gateway are also relevant for AAL and complement our findings; however, the methodology and the scope of the work differ from ours.

Avancha et al. [20] conducted a survey on privacy requirements of mobile computing technologies in the healthcare domain, using scenarios, an overview of the legal context (in the U.S.), a survey of existing health privacy frameworks for mHealth (mobile health), and a case study. Based on these, the authors propose a conceptual privacy framework for mHealth, itemize the privacy properties needed for such systems, and highlight some open research questions in the domain. The properties are similar to the principles of the GDPR that came into effect in the meantime (and the 95 EU Directive on data protection that existed at the time), and our findings show that many of these concerns are not yet solved for the AAL context, for instance issues around consent, transparency, and expression and enforcement of privacy preferences.

While the scopes and approaches of the above works differ from ours, our findings fit with theirs and there is an overlap in concerns of home IoT in general, implantable or body-area-networked devices, mobile health, and ambient assisted living in terms of system, security, and privacy properties, and general overall architecture.

8 Conclusion

We found that academic research and commercially available systems mostly go in the same direction when it comes to AAL architecture and used technologies. This is also true for the lack of privacy considerations: commercial systems as a group are not transparent about their data collection and handling when presenting their products on the web, and while a subset of academic research papers on AAL mention privacy as a potential concern, the subset is small and rarely goes beyond identifying the problem. Though there is no commonly accepted standard for AAL technologies, and IoT in general where there are several competing communication standards, we were able to abstract a common architecture that has the potential to be used for better privacy preservation. We found that most AAL health-monitoring systems had a centralized architecture, with a gateway mediating the communication between sensors and (cloud) servers for data processing. These gateways could be used for local computation and storage and thus enable data minimization already at the point of data collection. Using the architecture components, we also identified other intervention points for privacy preservation in AAL, e.g. the user interface for expressing preferences and consent for handling data. More than half of the papers in our survey were about IoT/cloud or machine learning alone, with the latter's part growing rapidly. Nearly as many papers contained a framework proposal as focused on a particular component. We expect that by mapping out the properties of current AAL research and technologies and their corresponding privacy concerns, we paved the way to make an appropriate selection of the aforementioned insights to be applied to the more narrow scope of AAL and to bring the remaining open problems into sharper focus for the research community. We suspect that due to the current pandemic-induced reduction of in-person social interaction overall and experienced difficulties in nursing homes specifically, trustworthy ambient assisted living systems are needed sooner than mandated merely by projected healthcare needs of an aging population. Disabilities or risk factors for infection, age-related or otherwise, contribute to the increased need for AAL.

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A Excluded Papers

Citation	Exclusion Criteria
Katsivelis et al. [76]	1
Son et al. [139]	2
Zhang et al. [163]	2
Lenca et al. [90]	1
Gupta et al. [62]	1
Rohit et al. [124]	1
Roy [125]	1
Jakkula [74]	2
Martonosi [97]	1
Zolfaghari et al. [166]	2
Pham et al. [118]	2
Oliveira et al. [109]	3
Yin et al. [161]	2
Reena and Parameswari et al. [123]	1
Warsi et al. [155]	1
Dobre et al. [45]	2
Haghi et al. [63]	2
Billis et al. [30]	2
Ahmed et al. [15]	1
Nussbaum [107]	1
Nussbaum [108]	1
Sixsmith et al. [136]	2
Trappeniers [146]	1
Shahrestani [133]	1
Klonovs et al. [81]	1
SPIMACS 09 [14]	1

Table 3: List of Excluded Papers

B Reviewed Papers

Category	Citations
Framework	Neagu et al. [105], Gomes et al. [59], Ruggeri and Briante [126] Kotronis et al. [84], Nguyen et al. [106], Shirali et al. [134] Suryadevara et al. [141], De Paola et al. [113], Nazário et al. [104] Alsibai et al. [17], Tragos et al. [145], Krishnan et al. [87] Lim et al. [91], Pham et al. [117], Hossain et al. [69] Biswas and Misra [31], Arcelus et al. [19], Vasilateanu et al. [151] Nazário et al. [103], Dohr et al. [46], Corotinschi et al. [40] Fabbricatore et al. [50], Morais and Wickstrom [43], Zhang et al. [165] Brink et al. [34], Giner et al. [58], Hossain and Muhammad [70] Wlodarczak et al. [156], Zhang et al. [164], Pham et al. [116] Wojciechowski [157], Hussain et al. [72], Laranjo et al. [88] Bentes [26], Valsamakis and Savidis [149], Chuang et al. [39] Seguin et al. [131], Titi et al. [144], Gaddam et al. [53] Wang et al. [154], Liu et al. [92], Hamim et al. [65] Yoo et al. [162], Hui and Kan [71], Petrakis et al. [115] Forkan et al. [52], Hassan et al. [67], Yao et al. [160]
Sensors, Actuators, & UI	Bui and Chong [35], Kearneyet al. [77], Taramascoet al. [143] Daviset al. [42], Grgurić et al. [60], Wuet al. [158] Kellyet al. [78], Smireket al. [137], Suryadevaraet al. [142] Prasadet al. [120], Barghet al. [23], Chandelet al. [37] Morandellet al. [100], Capodieciet al. [36]
Network Communication	Sobral et al. [138], Yacchirema et al. [159], Hail and Fischer [64] Palma et al. [112], Khoi et al. [80], Marinčić et al. [96] Ghayvat et al. [57], Cunha [41], Konstantinidis et al. [83]
Data Processing	Gayathri et al. [55], Oniga and Sütő [110], Prodan and Nascu [121] Tsirmpas et al. [147], Al Disi et al. [44], Vacher et al. [148] Jouini et al. [75], Ani et al. [18], K. R. et al. [122] Ghayvat et al. [56], Bae [22], Hassan et al. [68] Sebbak et al. [130], Koutli et al. [85], Mandarić et al. [95] Azefack et al. [21], Nandy et al. [102], Sarabia-Jacome et al. [128] Donaj and Maučec [47], Bianchi et al. [28]
Survey/Review	Duarte et al. [49], Knickerbocker et al. [82], Wan et al. [153] Chiuchisan et al. [38], Pal et al. [111], Ivanovic and Semnic [73] Pérez-Castrejón and Andrés-Gutiérrez [114], Hoof et al. [150] Begg and Hassan [25], Savage et al. [129] Leitner et al. [89], Beringer et al. [27]
Security	Doukas et al. [48], Porambage et al. [119], Massacci et al. [98] Khayat et al. [79], Koutli et al. [86]
Business Model	Bleja et al. [32], Grossmann et al. [61]

Table 4: List of Reviewed Papers

C Trend

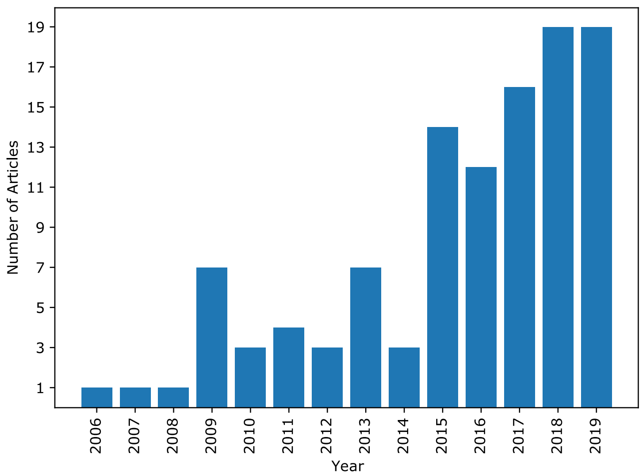

Figure 8: Research Progression of the Papers Under Review

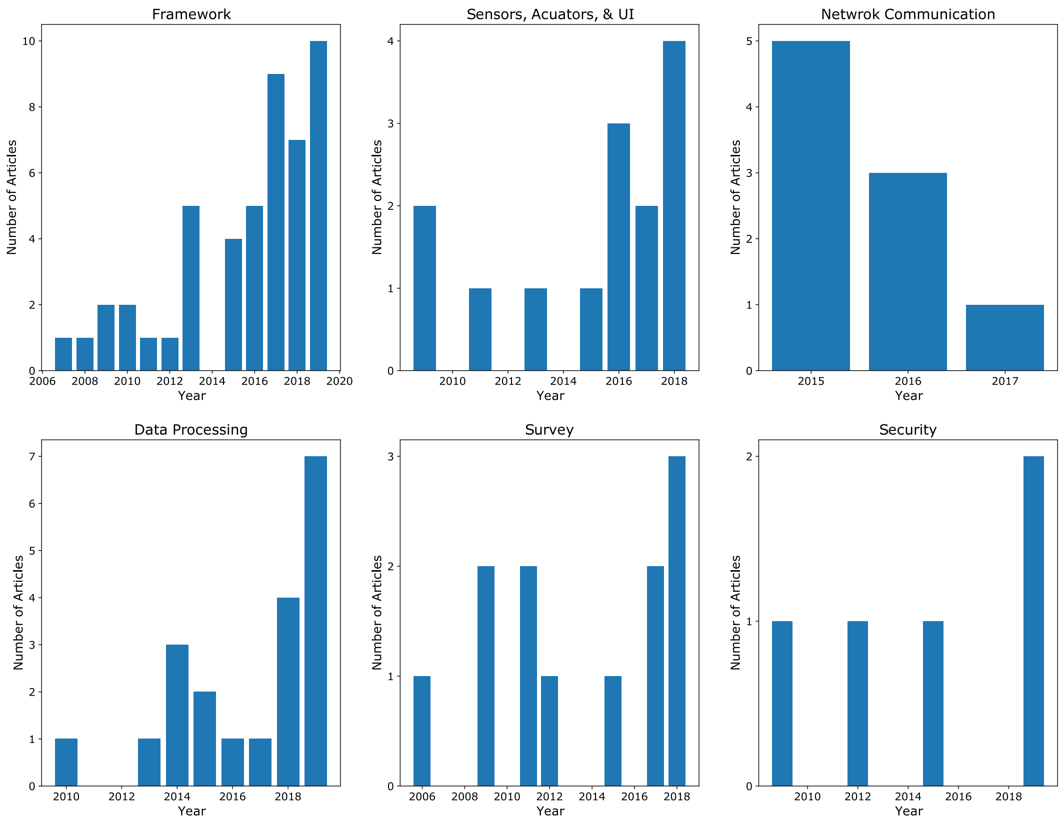

Figure 9: Category-wise Research Progression