Review Article

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Journal of Artificial Intelligence, Machine Learning and Data Science

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Vol: 1 & Iss: 3

Human-Robot Interaction: A State of The Art Review

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Citation: Yadeta DD, Bedane AB, & Chemma WD. Human-Robot Interaction: A State of The Art Review. *J Artif Intell Mach Learn & Data Sci*, 1(3), 109-118.

Received: 21 July, 2023; **Accepted:** 21 September, 2023; **Published:** 30 September, 2023

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A B S T R A C T

Due to the increasing impact of robots in our daily lives, Human robot interaction (HRI) is growing rapidly in various domains such as healthcare, military, industry, entertainment, service, agriculture, urban search and rescue, education, space exploration, and others. As a result, studying the status, trends, raising challenges, and future works of the HRI system is crucial. Many studies have been conducted on the state of the art of HRI systems, with hundreds of papers published each year on this issue. In this paper, after reviewing many research papers, we present application-based taxonomy, nature of robots, interaction between human(s) and robot(s), space/time taxonomy, and autonomy levels in HRI systems, as well as application of Artificial intelligence (AI) for HRI to provide an overview of the state-of-the-art. Finally, we develop four research opportunities based on the identified research gaps and challenges.

Introduction

Humans are intelligent at creativity and decision making, whereas machines are computationally intelligent[1]. As a result, combining this intelligence will result in advanced systems such as HRI. HRI is defined differently by researchers, is a field of study dedicated to understanding, designing, and evaluating robotic systems for use by or with humans, according to[2] in this definition interaction is defined as the necessity of communication between robots and humans. HRI is also defined by[3] as an interdisciplinary study of the dynamic interaction between humans and robots. In this definition, interaction refers to the process of working together to achieve a common goal.HRI emerged as a result of numerous workshops and conference tracks at the Association for the Advancement of Artificial Intelligence's (AAAI) Symposia Series, the IEEE International Conference on Robotics and Automation (ICRA), Robotics Systems and Sciences, the IEEE/Robotics Society of Japan International Conference on Intelligent Robot and Systems, the ACM International Conference on Human-Robot Interaction, the IEEE annual meeting, International Foundation of Robotics Research (IFRR) and European Land-Robot Trial (ELROB)[2]. Nowadays, HRI literature is rapidly expanding, with hundreds of publications each year and numerous professional societies and ad hoc meetings, mostly in the technical disciplines of mechanical and electrical engineering, computer and control science, and artificial intelligence[4]. The potential of robots to change our personal and professional lives by collaborating with humans in a variety of domains, as well as the growing trend, has boosted research in this area[5].

Various researchers presented a state-of-the-art review of HRI from a variety of perspectives, including application sector[6-17], safety[18], interaction experience[19-20], Human factor[4], task planning and programming[21] and problem-defining HRI[2]. Yanco and drury[22-23] proposed task specification and interaction behavior-based taxonomy to investigate the state of the art in HRI, but they left out the application sector. Dahiya[24] has done a survey on multi agent human robot interaction. Linda and Roesler[5] recently used improved taxonomy to structure and analyze HRI. However, the majority of the surveys we reviewed are focus narrowly and lack inclusiveness. While others are more generalized and lacking in detail.

The following are the main objectives of this paper: (1) providing an overview of the progress and status of HRI in various application sectors; and (2) highlighting HRI research challenges in various application sectors, and (3) analyzing the state-of-the-art in HRI from the nature ofinteraction point of view.

Several search engines were used for the literature review, including Google Scholar, Scopus, the AAAI website, and IEEE Xplore. HRI, robots Application, HRI taxonomy, and HRI application are used as keyword for our data collection. These search terms were used across all search engines. In all cases, the search terms produced a list of hundreds of possible articles. Which were presented in order of relevance to the topic. However, we chose top rated journals and refereed conference proceedings that publish HRI and robotics research. We primarily focused on IEEE, AAAI, ACM, and Springer conference papers on HRI and robotics, For the reason that the papers published at the above conferences have been peer-reviewed, are high quality, and have a particular focus on our topic. Then, for the state-of-the-art review of HRI, we identified and anlyzed 89 papers.

The paper is structured as follows: Section 2 provides a brief overview of HRI application-based taxonomy. Section 3 describes briefly the nature of robots in HRI. Section 4 discusses the interaction of humans and robots (s). Section 5 discusses HRI in the context of time/space taxonomy. Section 6 discusses the level of autonomy of HRI systems. Section 7 presents application of AI for HRI. Section 8 provides an overview of the state of the art in HRI. Section 9 discusses the challenges and future work in the field of HRI. Finally, conclusions are presented in section 10.

Application-based taxonomy of HRI

There are various techniques to study the HRI. In this section, we will use application-based classification to examine the current state of HRI development. Agah[25], Thomas[4] and many other researchers used this classification technique[5]. However, this classification method isn't preferred by other researchers[22-23]. The use of robots in various domains such as agriculture[7-8, 26], military[2, 16, 27-28], education[5, 9, 26], space exploration[2, 10-11, 29], urban search and rescue[2, 13, 22, 30-31], healthcare[5-6, 32-35] entertainment[2, 5, 22, 36-40], industry[7, 21, 41-43], service[5, 14, 15, 27, 32, 44], and others is rapidly increasing. As a result, discussing the status of HRI in these domains is necessary.

Military

The military is one use of robotics that meets the requirement that it be" dully, dirty, or dangerous" in the modern world. Applications might involve using remote vehicles in the battle to reduce risk exposure to soldiers or gathering data to support a risky task like a SWAT team take down[2]. In military, HRI plays a great role to make sure that the area is secured (free of enemy forces)[27]. A typical use of HRI in military application is in bomb disposal (called improvised explosive devices) and remotely controlled robots are frequently used to approach and evaluate suspicious packages[2]. According to US army Research Laboratory HRI enables the Soldier to use robotic systems to improve performances in the military domain[16]. Ketterbug[45], the first torpedo designed by USA engineers to attack an enemy by bomb disposal during WWI, is an early application of robotics in the military. Then, during WWII, remotely controlled and autonomous robots known as the German Goliath and the Soviet Teletank were developed[28]. Since then, there has been a significant increase in the use of robotics in military uses such as air, submarine, and ground[28]. The US army used ground robots such as Markbot, Packbot, and talon, observational aircraft such as RQ-11 razor and Foster miller talon, and unmanned aerial vehicles (UAVs) such as MQ-1, RQ-170 sentinel, and predator[28].

The robots in military domain equipped with lethal capabilities and programmed to execute orders issued by their users[46]. The orders to develop military robots may be formulated at a high and vague level, leaving a number of complex decisions and interpretations to the robot[46]. Even though moral responsibility is required in this domain, considering ethical and moral principles is one of the main challenges facing HRI in this domain.

Education

Although it is possible, learning through books and recorded lectures can be challenging and boring. Children with cognitive problems can't even benefit from this kind of learning. Almost often, learning is improved by interacting with a real-life teacher or co-learner. The robot has been considered when thinking about the future of education, whether to bring joy, act as an avatar to be taught or to speak, demonstrate a physical relationship (as in physics), or respond to student comments (with criticism or reinforcement)[26]. Robots can aid education in three ways:as learning tools or teaching aids, co-learners, and mentors[9].

Some examples of educational robots are: iCat robot[5] which helps children to remember vocabulary , Asimo robot[47] for cooperative learning, Nao robot[48] as a co-learner for children, Robot tutoring system[49] that recognizes a child's affective state and learns how to respond over long term interactions and fully affective social robotic champion, PopBots[50] a hands-on toolkit and curriculum that help young children to learn about artificial intelligence (AI) by building, programming, training, and interacting with a social robot ,and IRobot[51] that teaches funda- mental concepts of AI at high school level . However, understanding how people of various ages and abilities best learn from robots remains an important challenge to which human factors should contribute to some extent[9].

Industry

Robot based production is now an essential component of the industrial manufacturing infrastructure[41]. Industrial robots are designed to perform operations quickly, repeatedly, and accurately are usually suggested to a single physical location and manipulate objects on an assembly line[42], employed for tasks such as picking and placing in the production lines, stacking, parts assembly, casting, painting, sorting, welding, component soldering and so on[7]. Industrial robots are capable of performing a limited set of actions automatically based on a computer program, as wellas sensing its surroundings and its own joint positions and communicating this information back to a human operator who updates its computer instructions as required. These robots are called telerobots[4]. These robots were seen as substitutes and have been deployed to replace or assist humans in performing various repetitive, hazardous and tedious manufacturing tasks with a high accuracy[52].

Interaction with industrial robots is traditionally considered as a Human–Machine Interaction (HMI) because of their lower level of autonomy and complexity[53]. However, robots' functionality has evolved and they are still gaining more capabilities in order to achieve greater efficiency, autonomy, and safety[54]. Due to all these improvements industrial robots require differ interaction levels and which are identified depending on two principles[55]: (i) autonomy degree of the robotic system, and (ii) proximity of human and robot during operation. This enables HRI systems consisting of co-working humans and machines in production[54].

HRI in industry can be divided into three types based on four criteria[56]: workspace, working time, aim, and contact. Work space refers to the overlapping space in the working range of humans and robots as the common workspace. Working time is defined as the amount of time a participant spends inside the workspace. Every member of the interacting team has an aim in mind. Thisaim, like working time and workspace, can be compatible or incompatible with its counterpart. Asa result, if both entities share a workspace and act at the same time, the HRI can be classified as a Human-Robot Coexistence (HRCoex)[57]. Human and robot do not necessarily have the same aim in HRCoex[58], as they can operate on very different tasks, it is limited to collisions avoidance. In contrast, humans and robots are working on the same purpose in Human-Robot Cooperation (HRCoop) and fulfill the requirements of time and space at the same time, it is for collision detection and avoidance[56]. Lastly, Human–Robot Collaboration (HRC) is the feature of performing a complex task with direct human interaction in two different modalities[56]. (i) Physical collaboration where an explicit and intentional contact with forces exchange exists between humanand robot. (ii) Contact-less collaboration.

As collaborative robotics grow more widespread and allow for safe interaction between robots and humans, HRI is becoming easier and safer. In order to complete tasks in industrial environments, human and robot coworkers can now work side by side as collaborators due to industrial cobots[56]. Industrial cobots are utilized to assist coworkers with lifting, relocating production duties, and monitoring the assembly line. They can also support and relieve human operators, and place the loads quickly, precisely and safely[59].

Some examples for HRI in the industrial application are the robot workstation is running in the plant of BMW in South Carolina in which the robot helps human operators to perform the assembly of the final door, robot and the human workers cooperate in handling work-pieces, Repetitive co-manipulation tasks and for handling of heavy and bulky components in welding situations, the multi-robot system with collaborative functionality assists the worker[7].

Despite the fact that HRI is an advanced research field, industrial robots are still not autonomous enough to allow interaction at such levels. Ergonomics, flexibility, quality, and production cost drive HRI in an industrial setting. One of the challenges is the requirement for a modular system that includes both hardware and software. The most important modules associated with difficult issues in HRI are systems, sensors, integrated tools, and end effectors[21]. Future factorieswill need full production lines, including automation technologies that can be easily modified or repurposed as necessary, to compete in global markets[41].

Entertainment

Entertainment robotics is a growing field of human-robot interaction both in terms of application and research[2,5]. Early entertainment robotics focused on animatronics, in which the robot plays pre-recorded sounds that are synchronized with the robot's motion. The role of robots in this interaction is to present information. However, several robots designed to entertain were displayed at the 2005 AICHI Expo, including the use of robots as actors and dance partners[2]. This implies human role is minimized and robots becoming more autonomous. Some examples of currently available HRI systems in entertainment sector includes child-like humanoid robot Kaspar drumming robot[36], human-robot musicianship (shimon), human-robot theater stage performance[37], robotic weight loss coach[38], multiplayer game robots[39], Sony's Aibo entertainment robot[22] and educational play[43]. The concept of using live theater as a test bed for robot design and control methods is a newly emerging area of research[40].

Service

Service robots are a type of robot that must be able to handle unexpected situations in unstructured environments. Furthermore, they must be socially intelligent, meaning they must be able to fully comprehend the context and the people with whom they interact[14]. According to the International Federation of Robots (IFR), a service robot is one that operates fully or partially autonomously to carry out duties that are beneficial to the health and safety of people and other equipment, excluding manufacturing operations. HRI adds important multi modal issues such as acceptability, safety and communication for service robots that perform a wide variety of tasks[15]. HRI in the service domain has many applications including robots assisting elderly people[32] in their homes to find lost items like books, coffee mugs, or eyeglasses, information-kiosk robots[32] at an airport that engage people in conversations to get them to their destinations, Professional cleaning robots[5] for solar collectors or hoovering and lawn-mowing robots[27] for home use, and robots for elderly care. Star Wars robot R2D2[15], CoBot robots[60], NAO robots, and pepper robots[44] are some recent day application of HRI in this domain. How to formalize social norms and other behavior restrictions is one of the major challenges facing HRI in this area[32].

Space exploration

Robots have long been used in space exploration. Many precursor and early human missions will rely heavily on managed robots, but will also most likely include extravehicular activities. To prepare for these missions, NASA and other international space agencies conduct extensive field testing of both robotic and HRI technologies[2]. Many studies focused only on surface exploration scenarios while additional research is needed to identify other space exploration tasks that can benefit from HRI[29]. NASA has investigated HRI in space to prepare for future human exploration missions, achieving technology demonstrations of intra-vehicular robotic systems in space, including the Robonaut 2 humanoid and free-flyers, specifically the "Smart Synchronized Position Hold, Engage, Reorient, Experimental Satellites" (SPHERES) and Astrobee. Furthermore, astronauts have experimented with in-flight teleoperation of an external free-flyer, an Autonomous Extravehicular Activity (EVA) Robotic Camera (AERCam) Sprint robot, and a surface rover[10]. The successful integration of human and robotic technology is essential for both current and fu- ture human space exploration missions[11]. However, spaceflight present unique challenges for human-robot interaction and collaboration, including high communication latency's and limited bandwidth between non-collocated robots and humans, operation in reduced (or zero) gravity environments, and operation on other planetary bodies with associated issues due to radiation, temperature, illumination, dust, etc[12].

Healthcare

The use of social robots in healthcare is becoming more widespread as a result of a shortage of healthcare professionals, rising healthcare costs, and an exponential increase in the number of vulnerable populations such as the sick, the elderly, and children with developmental disabilities[6]. These robots have a wide range of potential healthcare applications, including surgery, health education, facilitating communication between patients and healthcare professionals, providing entertainment for hospitalized patients[33], medicine reminders and cognitive support[32]. But, the most well known health care applications are robot-guided surgery (e.g, Intuitive surgical Da Vinci surgical system and Magnetic Microbots), telepresence (e.g, RP-7)[34], and Assistive technology (e.g, iBOT wheelchair, manus and raptor robotic arms[35], pearl[6] and Seal Paro[5]). According to Marjorie and Huo[32] for the development of a successful HRI system in the healthcare domain, modeling a person's ability and personalizing the system are essential.

Urban Search and rescues

Urban search and rescue (USAR) is the emergency response activity that deals with the collapseof man-made structures[13]. In a USAR environment the robot should be able to recognize and react to the several types of uneven terrain, such as rubble[30]. The World Trade Center (WTC) disaster was the first known use of mobile robots for USAR. The WTC disaster demonstrated that small robots which can fit inside a backpack have a unique capability to collect useful data in USAR situations. Robots can enter voids too small or deep for a person, and can begin surveying larger voids that people are not permitted to enter until a fire has been put out or the structurehas been reinforced, a process that can take over eight hours. They can carry cameras, thermal imagers, hazardous material detectors, and medical payloads into the interior of a rubble pile far beyond where a bore scope can reach[13]. Another example is the integration of snake robots and mobile robots for disaster response[31]. Currently USAR performs many forms of dangerous tasks including dangerous material cleanup[22]. Due to the complexities of the tasks, USAR has a number of unresolved issues in mobility, sensing, and artificial intelligence. According to Murphy[13], the biggest obstacle to the development of rescue robotics is a lack of understanding of human-robot interaction (HRI). Many research efforts have recently expanded from ground robots to aerial robots used in natural disaster and wilderness search[2].

Agriculture

HRI is used in agriculture for a variety of tasks[7], and both robots and humans play important roles. Agricultural robots are typically autonomous or semi-autonomous systems that can solve challenging problems at various stages of the process. Agricultural robots have been successfully implemented for repetitive tasks such as land preparation, water irrigation and spraying, pruning, harvesting, monitoring and inspection, and mapping in order to reduce the farmer's workload and optimize process times and costs. In greenhouse applications, robots typically perform tasks such as grafting and cutting, weeding, harvesting and transplanting, precision spraying and irrigation, fruit and crop harvesting and detection, mapping, and color classification, among others. In some cases, a multi-purpose flexible robot can perform more than one task in a crop, improving horticultural and flower production and harvesting processes. There are currently few commercial robots working on agricultural issues, as the vast majority are still being developed as prototypes. Unmanned aerial vehicles (UAVs) or drones are other agricultural robotics development areas that have emerged in recent years. Drones have been used in a variety of applications, including geographic area monitoring, natural resource mapping, and surveying[8]. Thorvald robot[7], Agri Robot V1 and Vineyard Robotic sprayer[26] can be mentioned as examples of agriculture robots. However, agriculture is the most challenging domain for implementation of HRI system. Speciality crops (fruits and vegetables) and tasks such as pruning and thinning are too complex to automate completely[8].

Nature of robots in HRI

Many researchers presented the nature of robots in HRI in different ways of classification. While Linda and Roesler[5] describes robots in terms of task specification, degree of autonomy, and morphological classification, Yanco and Drury[22, 23] didn't briefly use the nature of robots as general classification criteria in their HRI classification work. In this section we are going to assess the nature of robots in the domain of HRI from a morphological and compositional point of view.

Morphology of robots in HRI

Robot morphology can serve as a classification base because robots can take various physical forms. Since the appearance of the robot can influence expectations about its functioning, communication styles, and modalities[5, 22-23]. Physical forms of robots in HRI can be categorized into anthropomorphic (human-like), zoomorphic(animal-like), and functional(technical) robots.

Anthropomorphic robots which have human-like physical form and users will expect natural language communication, competence, knowledge, and autonomy[5]. Female-like robots such as Tina, Erica, and Sophia and male-like robots such as Romeo, Yuri, and Albert are some examples of anthropomorphic robots[61].

Zoomorphic(animal-like) robots are mainly used in entertainment areas. For these robots, developing a relationship with humans requires a zoomorphic physical form[17]. Probo[62] hug- gable robot, Paro robot to improve the lives of elderly dementia patients by applying modern technology to medicine[63], Sony Aibo ERS-110, Leonardo, K-Team Khepera, I-Cybie, NeCoRo (Omron), Tama (Matsushita/Panasonic), and Me and My Shadow (MGA Entertainment)[17] are some examples of zoomorphic robots. Functional(technical) robots have neither anthropomorphic nor Zoomorphic physical form. Their physical structure and design are entirely determined by their operational objectives[17]. Healthcare, service, military, and industry domain robots are good examples of functional robots.

Robot Swarm in HRI

Robot swarms consist of multiple robots that coordinate autonomously via local control laws based on the robot's current state and nearby environment, including neighboring robots[64]. It's anothercrucial aspect of robotic systems in HRI which gets considerable attention in literature[23, 65]. It determines whether a robot team is composed of similar or different types of robots. A homogeneous team is a group of robots with similar hardware designs, manipulation capabilities, and interaction interfaces[24]. This robot team tends to have a single interface[23]. Homogeneous composition is most commonly seen in applications where groups of robots are viewed as individuals, such asa robot in a swarm or a human in a crowd. Additionally, homogeneous robots perform similar tasks, such as object transfers in a warehouse[24]. The heterogeneous team consists of different types of robots working together to make decisions in a variety of operations[23, 24]. The control and operation of a heterogeneous robot team is more difficult[24]. This type of robot team application is seen in inspection tasks in industry and fire commander game environments for research applications[66]. One well-known example of this type is the Swarmanoid heterogeneous mid-sized robots[67], which were created from three different robot types with complementary skills: hand-bots, foot-bots, and eye-bots.

Interaction between Humans and Robots

Researchers in HRI describe the interaction between humans and robots differently. Seraj et.al.[66] discussed the interaction between multi agents by using communication models and the agents involved in the system, while other researchers such as Yanco and Drury[22, 23] and Linda and Roesler[5] didn't use this general taxonomy; instead, they used more specific criteria. In this section we discuss the way that humans and robots interact with each other in HRI systems. This includes factors ratio and level of interaction, and role of humans and robots in the human robot interaction systems.

Level of interaction in HRI

The ratio of people to robots can't describe the interaction between humans and robots adequately. So levels of interaction should be considered to describe the interaction fully. There are eight levelsof interaction in HRI systems[22, 23].

1. One human to one robot: In this case, one human commands one robot, which transmits sensor information back to the human.
2. One human to robot team: In this case, one human commands a group of robots, issuing a single command that the robots must coordinate to fulfill.
3. One human multiple robots: One human controls multiple individual robots in this class, issuing multiple individual commands to robot that operate independently.
4. Human team to one robot: In this class, humans agree on commands and issue a single coordinated command to a single robot.
5. Multiple Humans to one robot: In this case, humans issue different commands to a single robot, which the robot must deconflict and/or prioritize.
6. Robots team to humans team: In this case, a group of humans gives a commands to a group of robots. The robots work together to determine which robot(s) will carry out, which partsof the command.
7. Humans team to multiple robots: In this class, a human team issues one commands to each individual robot.
8. Multiple Humans to robot team: Individual humans issue different commands to a teamof robots in this case, which the robots must, deconflict, prioritize, and distribute among themselves.

Role of Human in HRI

This role does not represent an actual interaction between a human and a robot, but rather a human action on the robot in terms of functional repair and maintenance (hardware and software)[5]. When interacting with a robot, Scholtz [19] describes five roles that a human may play: supervisor, operator, teammate, mechanic/programmer, and bystander.

1. Supervisory role: Involves monitoring the robot and giving instructions on how to accomplish the task[5]. This could imply that a number of robots are being monitored, and the supervisoris evaluating the given situation in relation to a goal that needs to be accomplished[19].
2. Operator role: The operator is called upon to modify internal software or models when the robot's behavior is not acceptable[19]. In order to modify abnormal behavior, change a given behavior to a more appropriate one, or take control and teleoperate the robot, an operator must work inside the robot, adjusting various parameters in its control mechanism[27]. Depending on the type of information provided to the operator for decision support there are four categories available: sensor information, sensor information provided, type of sensor fusion, and pre-processing[23]. Operating a bomb disposal robot and a Surgical DaVinci robot are two examples of situations in which the human role is always higher in the hierarchy than the robot[5].
3. Teammate role: A human collaborates with a robot to complete a joint task. The human has no managerial responsibility as a collaborator[5]. A manufacturing robot completing partof an assembly while a human worked on another part of the item's assembly is an example of this[23].
4. Mechanic/programmer: The mechanic deals with physical interventions, but humans must still determine whether the interaction has the desired effect on the robot's hardware or software[19].
5. Bystander Role: The human does not interact with the robot, but they share the same environment. To avoid collisions, even this human role requires a mental representation of the robot and its actions. The goal of the human role is avoidance[5]. For example, a person who walks into a room with a robot vacuum cleaner needs to be able to avoid the robot safely[23].

Role/task of robot in HRI

In HRI, for the classification and standardized comparison of various tasks across various application domains. Linda and Roesler[5] describe eight different roles for a robot: Exchange of information, precision, physical load reduction, transport, manipulation, cognitive stimulation, Emotional simulation, and physical simulation are all examples of simulations.

1. Information exchange: This task describes the robot's acquisition and analysis of information from the environment, as well as the transfer of information to the human. Mars missions or Search and Rescue missions are examples of this task.
2. Precision the robots perform tasks that are challenging for humans to perform (for example, micro-invasive surgery robots such as the DaVinci system that suppresses the surgeon's tremor).
3. Physical load reduction: The robot resumes tasks to reduce the physical workload of the human (e.g. lifting, carrying or fixing actions).
4. Transport: The robot is implemented to transport objects from one place to another (e.g. robots that carry parcels to different shelves in a warehouse, or robots carrying linen in hospitals from the patient rooms to the laundry).

5. Manipulating: The robot physically modified its environment (e.g. robots that perform welding actions on an object or pick and place robots).
6. Cognitive stimulation: The robot's aim is to engage the human on a cognitive level in the interaction through verbal or nonverbal communication. This task is often found in social HRI implemented in an educational setting like schools or kindergartens.
7. Emotional stimulation: The robot aims at stimulating emotional expressions and reactions in an interaction. Examples for this kind of robot are the robot seal Paro or other pet-like robots.
8. Physical stimulation: Physical simulation tasks are frequently used in rehabilitation settings. The Hirob robot from KUKA Medical Robotics is an example of this type of robot.

Time/Space Taxonomy

HRI researchers describe the time-space taxonomy's applicability in different ways. Yanco and Drury[23] and Ellis[68] et al. proposed that the time-space taxonomy could be applied to HRI. Linda and Roesler[5], On the other hand, did not include this taxonomy in their taxonomy. We discuss time/space in this section because it is useful to be able to discuss whether humans and robots are working together at the same time or at different times, in the same location or in different locations.

The time-space taxonomy divides human-robot interaction into four categories based on whether humans and robots use computing systems at the same time (synchronous) or at different times (asynchronous), and whether they are in the same place (collocated) or in different places (non-collocated)[68]. Mars Rover Fall is an example of a robot that operates in an asynchronous and non-collocated manner. Rescue robots are an example of a robot that operates in a synchronous and non-collocated manner. Robots on the factory floor are an example of asynchronous and col- located robots. Assistive robots, such as robotic wheelchairs, are examples of robots that operatein a synchronous and collocated manner.

Autonomy Level Taxonomy

Robot autonomy is crucial in HRI systems. Autonomy has been conceptualized in various fieldsin various ways. Autonomy in HRI has been largely explained as a function allocation between a human and a robot. Many researchers defined Autonomy as a system's ability to conduct its own operations and procedures[69-71]. According to Johniston[72] et al. Autonomy is the degree to which a robot can sense its environment, plan actions based on that environment, and act in response to that environment with the goal of achieving a task-specific goal (either provided to or created by the robot) without external control. Researchers in HRI used autonomy level classification of the HRI system[5, 23]. According to Linda and Roesler[5] and Beer[20] autonomy of HRI has four stages: information acquisition, information analysis, action selection and action implementation. Higher robot autonomy requires lower levels or less frequent HRI and higher levels or more sophisticated forms of HRI[20] and lower robot autonomy requires higher level HRI and less sophisticated forms of HRI. In this section we are going to study the status ofHRI by classifying them into 5 autonomy levels: teleoperation, mediated teleoperation, supervisory control, collaborative control, and peer to peer collaboration[2].

Teleoperation level: Teleoperation allows humans to act on and explore their environment froma distance. Concerned with the alteration of information available to the operator and its negative impact on task performance[73]. Master-slave handling device for manipulation of radioactive objects without exposing the operators, remote control of unmanned spacecraft, underwater robotic vehicles, and unmanned aerial vehicles (UAV) are typical examples of teleoperation levelHRI systems[4].

Mediated teleoperation level: This level of autonomy was proposed to improve the teleoperation system's stability and transparency[74]. Virtual reality mediated teleoperation[75] and robot mediated healthcare for infectious diseases[76] are typical examples of mediated teleoperation level. Human supervisory control level: Human operators are required at this level of autonomy for supervisory control functions such as planning, teaching, monitoring automatic control, repairing, learning from experience, and so on. Industrial robots performing assembly line tasks such aspicking and placing, welding, painting, and so on are examples of human supervisory autonomy[4]. Collaborative control Level: This level of autonomy implies some collaborative functionality between a human and a robot[77]. Using such autonomy level in HRI functionality is used to interact with a human coworker in a close and effective manner[78].

Peer to peer collaboration level: At this level of autonomy, humans and robots communicateas peers. Allowing robots to perform tasks on their own while also allowing them to request (and use) human expertise and assistance when necessary and getting robots to understand task-oriented commands in the same way that human teammates do are the major challenges in this autonomy level[79].

Artificial Intelligence (AI) for HRI

The most important and interesting areas of robots and HRI is the application of AI. Although intelligent computers may one day be able to "think" like a human, an intelligent robot could act and carry out all kinds of tasks in a human-like manner, which is essential in HRI[2, 80]. Speech recognition, dexterous manipulation, autonomous navigation, machine vision, pattern recognition, localization and mapping, along with abilities that are at the very core of advanced AI such as learning from experience and predicting the outcome of actions, are some of the AI-aspects that have a role to play in robotics and HRI[80].

HRI frequently uses concepts from AI in the design of autonomy algorithms. Moreover, AI techniques have been inspired by concepts from cognitive science. For example, the DIARC architecture for natural human-robot interaction integrates typical (lower-level) robotic capabilities for visual perception, laser-based mapping and localization, navigation, and others with (higher- level) cognitive capabilities such as robust incremental natural language understanding, task-based dialogue interactions, task-based planning, one-shot learning of actions and plan operators from natural language dialogues, mental modeling, and belief. It serves as a testbed for natural human- robot interaction[81]. Another example is the ACT-R system, a popular tool for modeling cognition that employs artificial intelligence-like production rules. Such cognitive models are becoming increasingly important in HRI, both as tools for modeling how humans might interact and as the base for generating robot behavior[82].

Machine learning is an AI sub-field that is very useful in robotics and HRI. Machine learning can be used to develop robot behaviors, robot perception, and multi-robot interaction[83]. Interactive learning has received attention as a way to capture and encode useful robot behaviors, to provide robot training, and to improve perception. Interactive techniques with intelligent systems are also present in AI. Interactive proof system, interactive planners, and "programming by reward" in machine learning are all examples of how human input can be used in collaboration with AI algorithms[84].

Natural language processing is another AI sub-field that is very useful in robotics and HRI. Effective and efficient HRI requires linguistic and ontological agreement[85]. NLP helps robots solve human language references to the real world application contexts. For instance, user utterances can be recognized using Automatic Speech Recognition (ASR) systems[86].

Augmented reality is AI aspects that have much importance to HRI. Augmented Reality (AR),the overlaying of computer graphics onto the real worldview, can provide the necessary means for grounding, situational awareness, a common frame of reference and spatial referencing for effective communication and collaboration[87]. Augmented reality techniques are used to support remote interactions in NASA's Robonaut[88].

Another AI-related area that are important in robotics and HRI is computer vision. Computer vision algorithms are frequently used to translate camera imagery into percepts that support autonomy. Moreover, these algorithms are also used to provide enhanced awareness of information through the use of image stabilization, mosaics, automated target recognition, and image enhancement[2]. For example, computer vision is used to analyze interactions between parrot-like robots and children, and features that can be used to distinguish autistic children from children with typical development (TD) are extracted[89].

Discussion

An application-based state-of-the-art review of HRI is discussed in this paper. We classified HRI systems based on the sector that they are implemented in. Agriculture, industry, military, education, entertainment, healthcare, urban search and rescue, space exploration, and service sectors are domains where HRI systems are mature enough to study the state of the art. We did not reviewed other domains because we did not have enough research papers to do so. HRI systems in agriculture, urban search and rescue, education, and space exploration are still challenging and at an infant stage, while increasing rapidly within industry, entertainment, healthcare, service, and military domains with some challenging problems. However, there are many future promises in these sectors, as ethical and moral values continue to be major challenges.

The nature of robots in the domain of HRI is discussed in this paper from two perspectives: morphological and compositional. Morphologically, robots can be classified as anthropomorphic (human-like), zoomorphic (animal-like), and functional (technical) and depending on their team composition, robots can be classified as homogeneous and heterogeneous in the context HRI. While robots take on human-like appearances, there are ethical and moral concerns about the human-robot relationship, and controlling and operating a heterogeneous robot team is difficult.

Furthermore, the nature of interaction between human(s) and robot(s) was studied to deter- mine the state of HRI. In this paper, the ratio of people to robot, the level of interaction, which classifies HRI systems into eight classes, the roles of human(s) such as supervisory, operator,mechanic/programmer, teammate, and bystander, and the roles of robot(s) such as information exchange, precision, physical load reduction, transport, manipulation, cognitive simulation, emotional simulation, and physical simulation in their interaction are assessed. The human-to-robot ratio does not describe the level of interaction; rather, it describes the number of robots and humans who took part in the interaction. The roles of humans and robots describe the task specification between human(s) and robot(s) in their interaction, which varies based on the autonomy level of the HRI system. While the level of interaction gives us information about the number of humans and robots participating in the interaction in addition to how information is exchanged between them.

We discussed the time-space taxonomy in this paper due to its importance and impact on the interaction. We divided this into four categories based on whether humans and robots use computing systems at the same time (synchronous) or at different times (asynchronous), andwhether they are in the same location (collocated) or in different locations (non-collocated).

We classified HRI systems based on the level of autonomy into teleoperation autonomy level, mediated teleoperation autonomy level, human supervisory autonomy level, collaborative control autonomy level, and peer to peer autonomy level to study its state of the art. In this section we conclude that higher robot autonomy requires lower levels or less frequent HRI and higher levels or more sophisticated forms of HRI system and lower robot autonomy requires higher level HRIand less sophisticated forms of HRI.

Finally, the application of AI in HRI is discussed from various aspects of AI, such as machine learning, natural language processing, augmented reality, and computer vision, as well as how AI can help design autonomy algorithms in HRI. In general, because of its focus on designing intelligence for human-built systems, the fields of artificial intelligence (AI) are important to thefield of HRI.

Challenges and Future Works

In this section, we will discuss the challenges in the revised research papers that we identified as research opportunities.

Safety issues of physical contact and moving within very close proximity

Currently, one of the emerging research ideas in this domain is addressing HRI safety issues. While conducting this survey, we encountered numerous safety issues that have arisen in the HRI research domain, particularly in the industrial, agricultural, and healthcare sectors. As mentioned in Section 2, robots can perform a variety of industrial tasks, but collision avoidance is still an issue in this sector. The same issue is raised in agriculture and healthcare sectors. Inclusiveness of abstract ideas that requires reasoning for the results in addition to learning experience, planning, teaching, monitoring of automatic control, making repairs, and learning from environment complicates the issue. Incorporating symbolic method for reasoning the results and sub-symbolic method for learning from experiences should be studied to solve the problem.

Personalization of HRI systems

Personalization issues have arisen in a variety of sectors due to the rapid growth of HRI. As discussed in the application-based taxonomy section, personalization of HRI systems is required when considering a person's ability in healthcare and understanding how people of various ages and abilities best learn from robots in education. Personalization can also increase user satisfaction from robot services in the service and entertainment domains. To personalize HRI systems, we need to study and understand more about personal characteristics and how to adopt them in HRI systems.

Standards for HRI systems

According to our findings, even though ISO developed HRI safety standards for the industrial, healthcare, and service domains, there are no standards in agriculture and insufficient standards in the other domains. It is critical to develop and implement both ethical and practical standards in order to increase the safety, usefulness, acceptability, appropriateness, and decrease the fear of using HRI systems. To develop standards for HRI systems, we should further investigate practical and ethical challenges in these domains.

Communication related issues

According to our review, communication is the key to human-robot interaction; as a result, several verbal and nonverbal communication modalities have been developed to enable effective communication between humans and robots. There are also efforts to develop robots capable of recognizing human gestures and facial expressions, as well as producing eye gazes. Despite enormous advances in the equipment of robotic agents with socio-cognitive capabilities, attempts to improve mutual understanding between humans and robots have not been successful. To address this issue, more research on supporting effective interaction through cognitive and emotive computing, as well as natural interaction, is needed.

10 Conclusion

Human robot interaction (HRI) is a field of study dedicated to understanding, designing, and evaluating robotic systems for use by or with humans. HRI is growing rapidly in various domains such as healthcare, military, industry, entertainment, service, agriculture, urban search and rescue, education, space exploration, and others, because of the increasing impact of robots in our daily lives. Application based taxonomy, nature of robots, way of interaction between human(s) and robot(s), time/space taxonomy, and autonomy levels can be used for studying state of the art ofHRI systems.

According to our review of the state of the art in HRI systems, major challenges in this domain include physical contact and moving within very close proximity, personalization issues, a lack of standards, and communication-related issues. Depending on these challenges, we proposed future works to address these issues.

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