Robotics Architectures Based Machine Learning and Deep Learning Approaches

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Abstract: Robotics has been playing a vital role in our daily lives with a wide range of applications to improve the quality of life. With a variety of usable applications in the medical, manufacturing, and transportation industries, there is a continuous need for improving the performance of robotics for the importance of precision in executing commands and tasks. The implementation of precise commands has led to intense research on approaches to improve the performance of robotics. Machine Learning (ML) and Deep Learning (DL) have been drawing attention to applying architectures and algorithms to robotics which imposed a positive impact on the field of robotics. ML and DL applications in robotics include areas of computer vision, imitation learning, self-supervised learning, assistive and medical technologies, multi-agent learning, and manufacturing. This paper provides a comprehensive review of autonomous vs automatic robotics, robotic applications, extreme learning machine methods, and ML for soft robotics applications, in addition, to discussing the challenges, and future trends for AI applications in robotics applications.

1. Introduction

Nowadays, robotics has become an advanced technology and the most widely used in many fields. Modern robots have relied heavily on artificial intelligence, which makes them more perceptive and interactive [1]. Machine learning (ML) and deep learning (DL) methods helped to develop solutions to a number of problems facing robotics applications, adding learning methods in real-world environments, in addition to designing high and intelligent control capabilities [2]. In recent years, a number of robots have been developed using artificial intelligence techniques, which made them able to increase interaction, human capabilities, and productivity, in addition to enhancing human-like cognitive abilities.

In the field of robot design, event control is one of the complex operations that are difficult to design through code, due to the difficulty of translating and analysing the natural event, especially when there is a large variety of operations performed by the robot in the real world [3]. Therefore, the process of designing robots needs algorithms that have the ability to build expert human knowledge of the robot as structured parameters and improve control strategies. According to these rationales, there is a need for frequent changes in the programming of the robot due to the environmental changes surrounding it and the need for a complex analytical model to form software solutions [4]. Therefore, the use of machine and DL models is one of the techniques that can deal with these complexities in a wide and unique way.

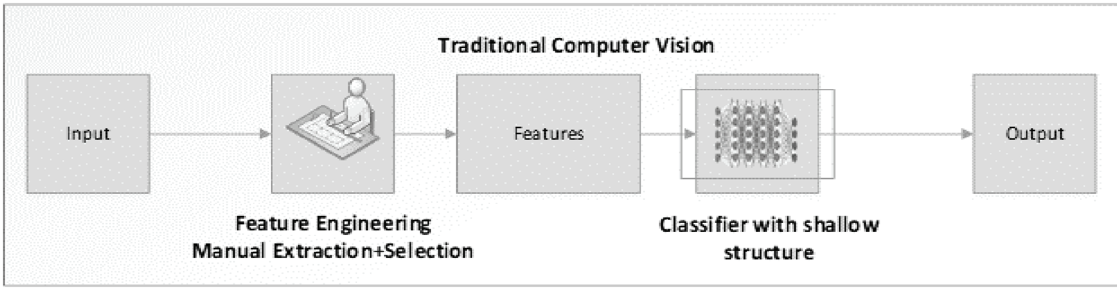
The main motive behind the use of the machine and deep learning in robots is because they are more general and deep networks are able to think and abstract at a high level and are ideal for robots in an unstructured environment [5]. This paper presents a survey of the applications of machine learning and deep learning in the field of robotics, as it presents the technical and applied concept of these technologies in a number of applications such as computer vision, assistive and medical technologies, multi, self, and imitation learning approaches.

2. Robotics general applications

Robotics have been contributing to the development of today's technology and the next generation of technologies by adding applications that improve the performance of many fields with innovative involvement of ML in a variety of applications including computer vision, imitation learning, self-supervised learning, assistive and medical technologies, and multi-agent learning.

2.1. Computer Vision

Machine learning is needed when it comes to complex digital image problems such as (image segmentation, detection, colorization, and classification).



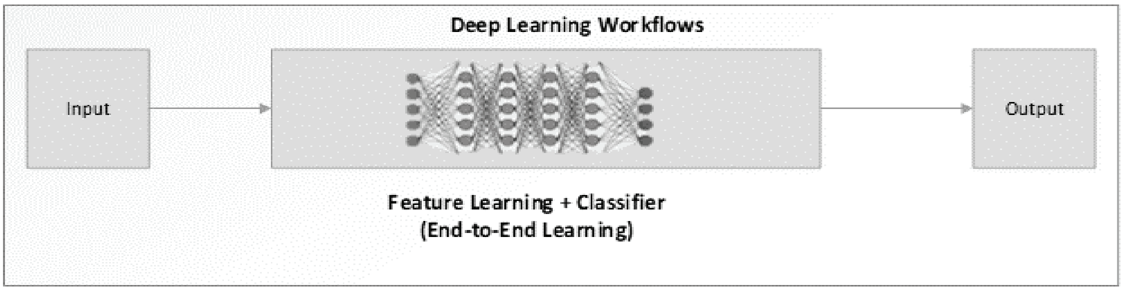


Fig 1. Traditional Computer Vision vs. Deep Learning Workflows

ML mechanisms such as Deep Learning (DL) approaches represented by Convolutional Neural Networks (CNN) had proven results in improving prediction performance using various resources. DL is a branch of machine learning which is mainly built upon Artificial Neural Networks (ANN) which imitate the function of the human brain [6]. CNN consists of multiple layers in the network, where data is pre-processed through several steps including mean-subtraction, normalization, PCA whitening, and local contrast normalization for the purpose of preparing data to be processed in the network [7]. Fig. 1 compares the traditional computer vision from deep learning-based computer vision.

2.2. Imitation Learning

In the early 60s the concept of a robot holding objects with the industrial robot unmated used a two-finger robot to hold wooden blocks and organize them on top of each other, the purpose of designing such a robot was to imitate a human function. Thus, a great number of research was conducted to improve the holding and manipulation mechanisms [8]. Imitation learning which is also referred to as learning from demonstration (LfD) is a concept that has a very strong presence in performing complex manipulation tasks which recognize and replicates human motion without the need for complex behaviour programming [9].

Deep Reinforcement Learning (DRL) adds a huge value to the field of manipulation learning for its properties in producing policies independently, which is not obtained by the traditional manipulation learning methods where the whole model of the learning system much be known in advance. Deep RL merges the perception ability and decision-making which lets the robot directly learn the actions from an image [10]. The foundation of reinforcement learning is the Markov Decision Process (MDP), the result of the action state function can be produced by the expected sum of rewards by the function.

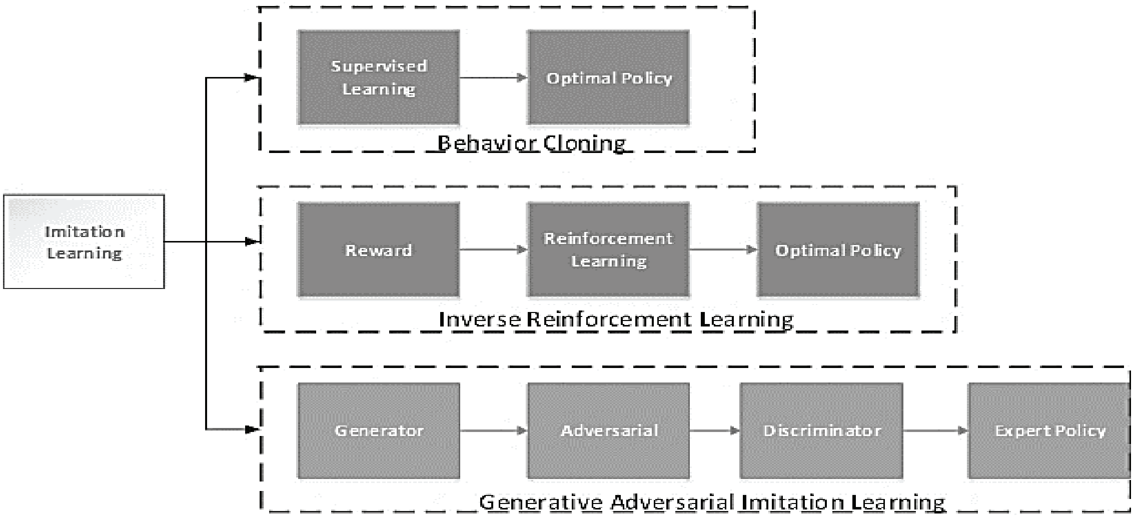


Fig 2. Imitation Learning Classification

Imitation learning is the concept of imitating the instructor's behavior or motion, a robot learns movements by observing the expert's demonstration in this process. In this learning process, the robot also learns to compare the observation with the performance in order to improve the learning process [11]

Data can be trained from ready samples instead of learning the entire process from scratch, this has improved the learning efficiency. The speed and accuracy of imitation learning can be elevated by using a reinforcement learning techniques combination [12]. Imitation learning is currently classified into three main categories: (a) behavior cloning (BC), (b) inverse reinforcement learning (IRL), and (c) generative adversarial imitation learning (GAIL). These categories are further elaborated in Fig. 2.

In behaviour cloning the learning, the procedure takes after policy learning which means enabling the distribution of state-action trajectory which the agent generates to match the known teaching trajectory [13]. Traditionally the learning procedure is to make the robotic arm or object repeat a certain motion by manual guidance or a teaching box, thus it can only repeat the motion which it previously learned, rather than adapting to an unknown environment change. With the introduction of data-driven machine learning techniques, the robot can identify basic units of robot manipulation and adapt to environment changes [14].

2.3. Self-Supervised Learning

Self-supervised learning has been used to improve the performance of many aspects of robotic applications such as improving robot navigation, manipulation, and visuals. Most robots navigate through analysing information from sensor data as they depend on pose information for effective manipulation and task completion. Robots take their pose information using external sources such as GPS and motion-capture systems, or by using onboard sensors which are currently gaining popularity such as 3D LiDARs which registers different distances to help robots gain their pose information [15]. Self-supervised learning is an effective learning approach as the robot does not have to be supervised and the target does not need to be labeled. Thus, self-supervised learning is most suited when the data under investigation is unlabeled. [16]

Integrating image domain adaptation into a self-supervised training process for the purpose of feature extraction using the domain-invariant function, the image is translated into different domains, and let the network train upon a certain function to find correlated key points. In order to minimize the matching loss, we use optimization for feature detector and descriptor instead of domain translation which leads to obtaining an improved feature extraction function [19]. This process has increased the performance of the system by letting the feature extraction train on different domains which allows; therefore, the network learns to filter key points and match them under changing conditions. The cross-domain concept is done under deep convolutional layers which shifts the learning process to a bigger space, considering that we are using objects and scenes instead of a single image space. Using image-to-image translation makes feature extraction more powerful when a set of conditions is under examination [20].

2.4. Assistive and Medical Technologies

Assistive Technology is a concept that describes applications aimed at supporting older people and those with long-term disabilities to overcome their functional absence or decline. The need for assistive technology has been growing which led to the need for improved performance to meet this growth. Today's advancements in machine learning allowed the development of autonomous robots which can adapt, respond, and interact with their environment [21]. This adaptation has led to enhanced human-machine collaboration in terms of building companion robots, autonomous vehicles, and exoskeletons, companion robots perform certain tasks which are meant to improve patient's quality of life by health and emotional monitoring, entertainment, and communication and assisting [22].

Applying care robots mainly aim at the human-robot interaction, which leads to a careful and thorough consideration of the background of the users of these robots. The users lack a technical background in robotics, their background is usually from the medical field such as nursing science, gerontology, and medicine. When designing such a system, the nursing staff or relatives are an integral part of the design process, as they are considered a secondary use for the Assistive Technology as the primary user [23]

The use of convolutional Neural networks as a part of the Deep Learning approaches has contributed to the elevation of Assistive Technology performance by using Part Affinity Field (PAF) for human body state prediction after carefully analysing human images. PAF method has qualities of high precision and high efficiency, it can efficiently detect a 2D position of a human body by analysing an image [24].

2.5. Multi-Agent Learning

Applying learning-based methods to serve multi-robot planning showed promising results for their characteristics of effectively handling high-dimensional environments with state-space representations. The use of reinforcement learning in the robotics field solved issues of having multiple robots i.e., multi-agents learn to perform a task at the same time. [25]. Multi-agent systems must develop approaches to overcome issues of energy consumption and computation by offloading the computation to the cloud. Integrating technologies such as multi-robot systems with edge and cloud computing has impacted the performance of multi-agent system performance significantly, by adding value to the whole approach in improving user experience [36].

3. Machine Learning Based Robotics Applications

Robotics is a field that is rapidly developing by adding advanced sensorimotor functions that can give a robot the ability to adapt to the changing environment, this is achieved by the application of AI within robotics by optimizing the level of autonomy by learning using machine learning techniques [28]. The success of adding intelligence to machines is measured by the ability to predict the future by planning how to perform a task and interacting with the world through successfully manipulating or navigating.

3.1. ML in Robotics Recommendation Systems

Today's growth in every aspect of life dragged attention to the need for better decision-making processes when addressing e-services to improve the decision-making for customers. These systems use personalized e-services which employ the techniques and mechanisms with an artificial intelligence background, by means of user profiling and preference discovery [29]. The use of various machine learning techniques increased the level of quality of recommendations and improved user satisfaction. The recommender systems are primarily devised to assist individuals who are short on experience or knowledge to deal with the vast array of choices they are presented with these systems operate by predicting use preferences that are a result of analysing information from several sources. Recommender systems are divided into three types, content-based recommender systems, collaborative filtering-based recommender systems, and knowledge-based recommender systems [30].

Content-based recommender systems aim at suggesting items similar to items that previously caught the attention of a certain user. Documents or illustrations are used to extract item properties using retrieval techniques such as the vector space model [31]. This creates a user profile that contains information about their preferences i.e., what the user likes and dislikes. Collaborative filtering-based recommender systems are the most applied technique in recommender systems as it is the most popular, the main assumption to base CF technique is that similar users will consume similar items, and a system that is based on user preferences will operate on information on users who have similar interests. CF techniques are divided into two categories, memory-based CF and model-based CF whereas memory-based in the early generation is based on heuristic algorithms to calculate similarities between users and items. As a result, memory-based can also be divided into two parts user-based CF and Item-based CF, the main algorithm used in memory-based CF is the nearest neighbour which is simple, efficient, and accurate [32].

Model-based CF is used to predict user behaviour using machine learning and data mining methods, this approach was proposed as a solution for the limitations of the previous approach, but its use has expanded to serve other applications. Knowledge-based recommender systems are formed around the existing knowledge about users, it is based on knowledge about users that is extracted from their previous behaviour [33]. Knowledge-based uses a common technique called case-base which is the employment of previous problems to solve the current problem. The application areas of knowledge-based are house sales, financial services, and health decision support, these types of application areas represent a unique problem and are known to be highly specific domain knowledge.

The application of AI methods has improved the performance of these techniques which cover areas of knowledge engineering, reasoning, planning, communication, perception, and motion [35]. In simple words, recommender systems are used to predict what your customer want by analyzing their behavior based on previous actions [36].

In qualitative evaluation metrics, there is a wide range of performance evaluation approaches where the simplest way is Root Mean Square Error (RMSE) which is widely used to evaluate the prediction accuracy. This evaluation is achieved by taking the square root of the mean square error (MSE) which is calculated by dividing the sum of squares of the difference between the actual grade and the predicted grade by the total number of grades predicted [37]. Other qualitative evaluations include precision, recall, accuracy, F-measure, ROC curve, and Area under the curve (AUC) all of which are covered under a confusion matrix aimed at calculating the value of the qualitative evaluation index. This matrix enables the evaluation of a recommender system by measuring whether the user's preference is based on a recommender system. Each row represents user preferred item add each column represents if the recommender model has recommended the related item, this is elaborated in Table 1 [38].

Table 1. Qualitative Evaluation Matrix – Confusion Matrix

Preference	Recommended	Not Recommended
User-preferred Item	True Positive (TP)	True Negative (TN)
User-Non-preferred-item	False Positive (FP)	False Negative (FN)

Where: TP represents the number of items that matched user preference

3.2. ML in Nano Health Applications

Nanotechnology is developing rapidly with the advancements of robotics and ML applications toward smart life. Nevertheless, nanotechnology is still in its beginning, which has drawn the attention of researchers to develop this field. The term nano refers to the development of devices that are smaller than the diameter of hair [39]. Nanotechnology involves the process of designing, fabricating, and manufacturing materials at the nanoscale. Robotics can be incorporated into the nanoscale as well which can then refer to as nanorobotics. Defined nanorobotics as Nanorobots are devices capable of sensing, actuating, signalling, processing information, intelligence, or exhibiting swarm behaviour at the nanoscale [40].

The application of Machine learning has improved the performance of Nano health applications, by adding value to image processing by applying recognition, clustering, and classifications of images by means of medical imaging processing using ML. The use of microscopic images incorporating ML into biological analysis increases the improvement of disease identification [42]. ML increases comprehension of the effect of nanoparticles on their characteristics and their interaction with the targeted tissue and cells, ML algorithms have been used to predict the pathological response to breast cancer treatment with a high accuracy rate. Making use of algorithms that does not require large data sets is viable when using artificial neural networks which improved the prediction error rate [43].

3.3. Dynamic Traffic Robotics Control

The recent advances in robotic applications have led to the development of automated guided vehicles (AGV) which evolved into autonomous mobile robots (AMR). The main part of AGV material handling systems has developed through different milestones of mechanical, optical, inductive, inertial, and laser-guided which evolved into today's vision-based system [44]. These systems take advantage of technologies that improve the performance, these technologies such as sensors, powerful onboard computers, artificial intelligence, and simultaneous location and mapping, which enables the robot to comprehend the operating environment [45].

AI techniques are added to AMRs to improve navigation, they navigate autonomously in an unpredictable environment. There are a variety of ML techniques that help to identify and classify obstacles, examples of these techniques are fuzzy logic, neural network, genetic algorithm, and neuro-fuzzy. All these techniques are popular for moving the robot from one point to another while avoiding a collision. These techniques are inspired by the ability of the human brain to perform certain tasks [46].

Designing a control algorithm required a dynamic system, if we consider a dual-arm robot we can design and analyse a control algorithm for the dual-arm robot oscillation, position, and speed control. The system design introduces time delay control and pole placement-based feedback control to control the oscillation (angular displacement) and precise position and speed control respectively.

4. Challenges And Open Issues in Robotics Applications

Robotics applications have become a vital aspect of our daily lives, adding robotics to homes, factories, the health sector, driving vehicles, and education. Applying robotics is rapidly developing to combine other applications with the employment of machine learning approaches to improve performance including accuracy, efficiency, and security [47]. Open issues available in research extend to include the type of learning to use, ML application, ML architecture, standardization, and other performance evaluation metrics besides accuracy.

Supervised learning is the most used type of learning in the robotic application, exploring other types of learning approaches will add value to the improvement and performance. Adding ML applications to cover the issues caused by the use of radio access causes multipath which degrades the performance of the system [48]. Trending use of DL architecture in robotics and especially localization but the limitation of DL architectures is the large amount of training data required which is not easily obtained. Standard performance evaluation parameters are limited, therefor identifying practices in evaluation parameters is a vital issue to study, exploring another evaluation parameter to test the performance of ML architectures is necessary [49].

ML applications have a vast implementation range that covers areas of health, wellness, security, forensics, and energy management. As ML and robotics are rapidly evolving, emergent trends in these areas require further studies [50]. Trends include empowering end-to-end automated, ubiquitous, and continuous deep learning approaches for data-driven intelligent systems. Rapidly growing technologies in 5G, cloud computing, and blockchain represent new opportunities for improving the overall system. User privacy, security, and safety represent challenges that much be addressed. Black box smart systems present opportunities in AI health applications for their properties of low-cost deployment, fast performance, and accuracy, this will help in health applications in monitoring, rehabilitation, and diagnoses [51].

5. Conclusion

Machine learning plays important role in multiple areas of robotics as discussed in the paper, autonomous robotics added value to various applications involving the automation of processes such as manufacturing, health application, IoT, and autonomous vehicles. ML was also incorporated in many applications such as computer vision, and assistive technologies to improve the quality of giving care to patients and imitation learning. Extreme learning machine methods solved the limitations of gradient-based learning algorithms in terms of classification efficiency. Soft robotics added abilities that were not available in rigid robotics which are the flexibility and adaptability which made the performance of robots move toward human-like responses and gestures.

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