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Design and Implementation of a Non-Invasive Wearable Monitoring System for Individuals with Autism Spectrum Disorder using Digital Twin Technology

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ABSTRACT: Through this paper a novel solution for the mental healthcare, autism spectrum disorder (ASD) has been provided with the help of artificial intelligence (AI), digital twin, virtual reality (VR) and micro-electro-mechanical systems (MEMS). The major reason of choosing the digital twin is because of its virtual representation of individuals, which makes the process clear and comfortable. Nowadays, the use of virtual reality which is emerging as one of the promising and satisfying instruments for children those who are badly affected with autism spectrum disorder. The reason of using this concept is VR offers immersive and controlled environments that enable children to practice social, emotional, and behavioral skills without real-world pressure. Studies report improvements in social engagement, emotion recognition, and self-regulation through VR-based interventions. Here, the major role of MEMS sensors is to collect the emotional signals through the different movements, skin responses and heart rates. AI makes this process easy especially due to its data analysis process. However, challenges such as small sample sizes, high costs, technical limitations, and the absence of standardized intervention protocols restrict large-scale adoption and consistent evaluation etc. makes this process difficult. But despite these limitations, VR demonstrates strong potential as a supportive approach for ASD therapy, particularly for structured social skills training with the help of high-quality sensors and AI analysis report. The major objective of this paper is to provide a unique solution using MEMS sensors with the help of AI and digital twin for the emotional skill enlargement. The major technology which has been used in this entire process is artificial intelligence,

digital twin and MEMS sensors for making the process trustable and technically strong. Additionally, during the analysis process there is a great role of COMSOL Multiphysics as well as some open-source tools like circuit verse, tinker cad etc.

INTRODUCTION

In this research work with the help of artificial intelligence and MEMS sensors one of the very common problem which is known as autism spectrum disorder is addressed. In short it is known as ASD which influences social collaboration, communication, and emotional recognition, presenting challenges for traditional therapies due to the complexities of real-world environments[1].

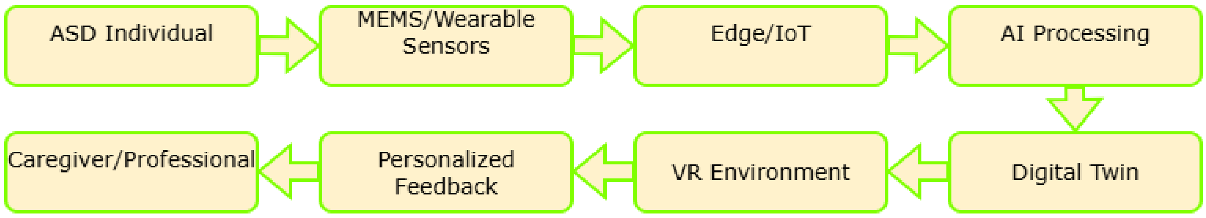

Fig. 1 Basic concept of the research work

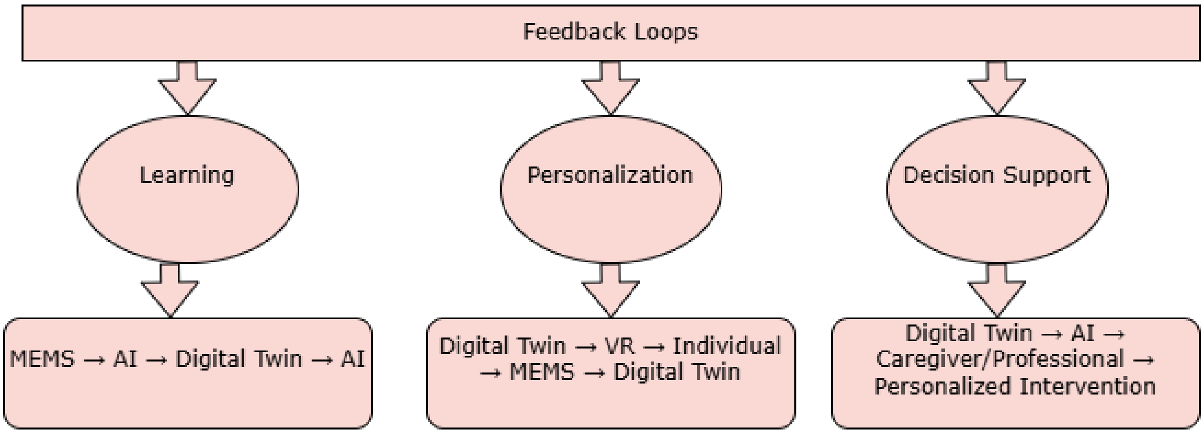

Fig. 2 Major feedback loops of the applied technologies

In Fig.1 and Fig.2 the basic concept of research work and applied technologies in three different stages has been shown for the clear understanding. As it is a well popular fact that Virtual Reality in short VR has arisen as a promising therapeutic tool, providing controlled as well as immersive situations where individuals with ASD can practice social and emotional skills without social pressures[2]. This paper examines VR's potential to enhance these skills in children with ASD by reviewing recent studies and multimodal data from VR systems, such as eye tracking and physiological measurements[3]. This work also addresses the challenges of current VR applications, including high costs and standardization issues, aiming to assess VR's feasibility as an impactful intervention for ASD therapy[4].

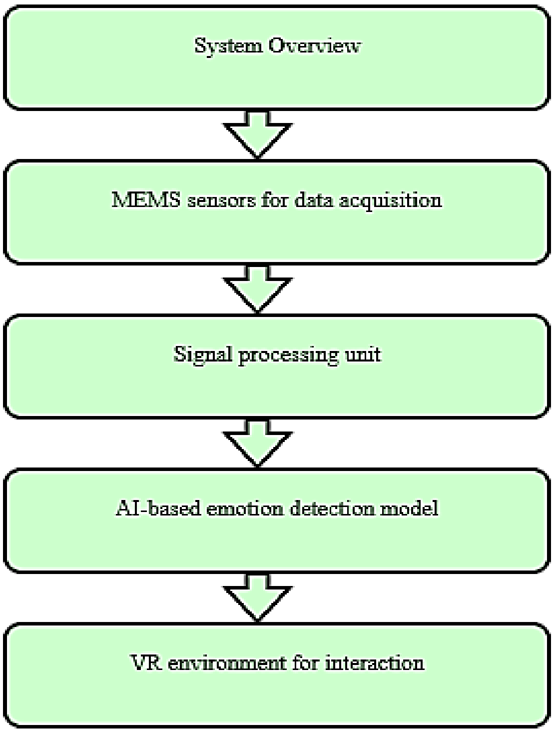

Fig.3 Proposed system overview

In Fig.3 the major functions have been shown about the role of MEMS sensors[5], AI and the necessity of VR. Major objectives of this paper are to provide a system through which a continuous and secure monitoring the virtual reality which helps the enhancement of emotional skill development at different platforms[6]. The major outcome of this paper is based on the detection of emotional responses a good mental health treatment can be provided. The major reason of making use of MEMS is its small size, diversity, cost and reliability[7]. There are many analyses which have been done using COMSOL Multiphysics, specially for understanding the nature and properties of MEMS sensors[8]. These sensors provide the good responses towards motion, heart rate, skin-based responses or conductance etc. Additionally due to AI model data analysis is one of the major tasks which have been performed using machine learning algorithms[9].

LITERATURE REVIEW

There are lot of surveys and study has been done on this and it has been observed that many research has been done on this but still lot of things are lagging and MEMS based sensors have the enough capabilities to provide the good input through its good detection and response ability. Additionally, machine learning models make this much useful. In current years, VR has developed as a promising tool for therapeutic interventions in ASD. VR provides interactive and simulated surroundings where children those who have ASD can exercise social and behavioural skills tailored to their individual needs. With the help of literature survey an analysis of growth rate has been done for the AI, VR and MEMS, over the years which have been shown in Fig.4. Additionally, it has been noticed that there are several people given the notable contributions in this field. Especially, Sandra Cano provided a good input for the wearable devices[10]. Mohammed Taj-Eldin contributed a lot for the physiological analysis[11] it's much useful here especially for ASD. Sarah Alhassan justified a very good approach about the edge sensing[12], which is much applicable for this kind of research. Similarly, Patricia Mesa-Gresa provided a detail about the VR Components[13]. Actually, it's a huge field with lots of contributions. So, for making the process understandable one block diagram has been shown in Fig.5 which is given below.

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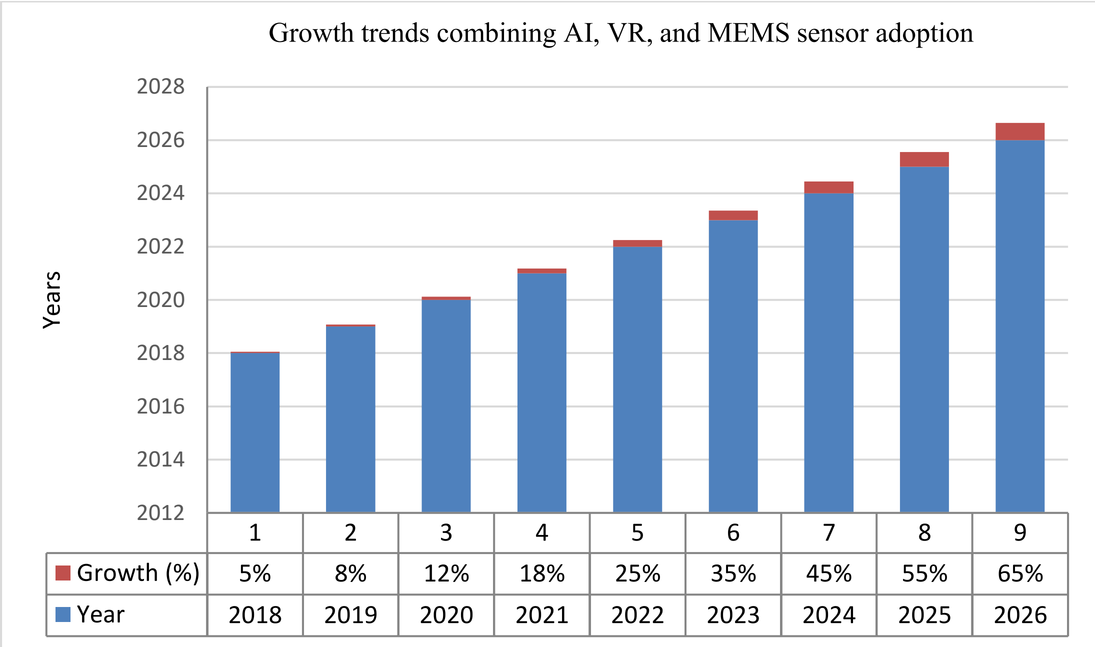


Fig.4 Literature review and growth of AI, VR and MEMS sensor adoption

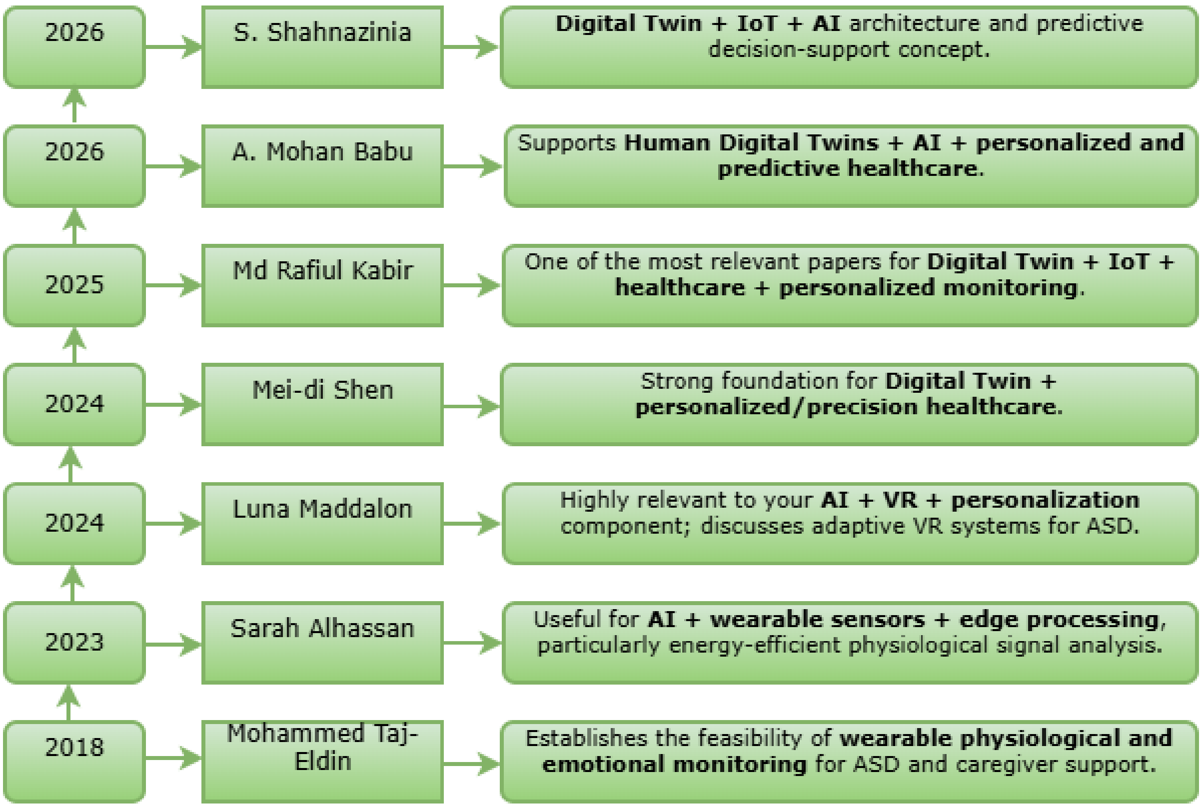


Fig.5 Major Contributions over the years

Finally, from the detail analysis of the literature survey it is clear that there is huge scope of research in this field due to its multidisciplinary nature[14]. So, currently this field is booming due to the major supports of AI and digital twins and micro devices especially for the wearable kind of things[15].

RESEARCH METHODOLOGY

To achieve the same a systematic selection process has been applied, focusing on peer-reviewed studies that reported measurable outcomes related to social skills, emotional engagement, and behavioural adaptation[16]. It has been noted that in many cases only studies were employed only for the VR concept-based interventions specifically designed for the kids who is affected due to ASD were included.

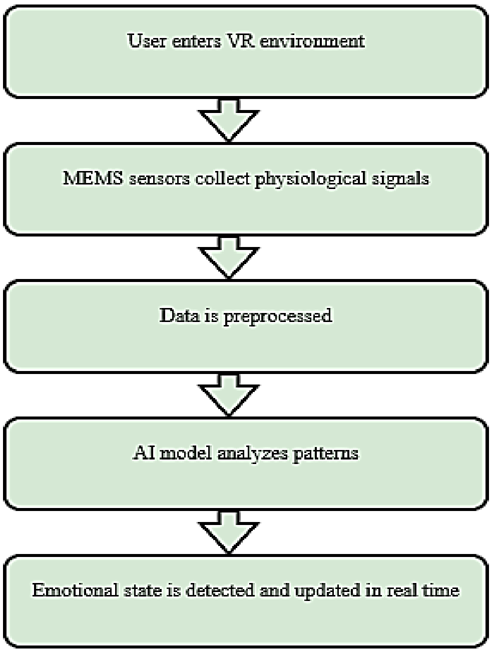


Fig.6 Research flow and technical process

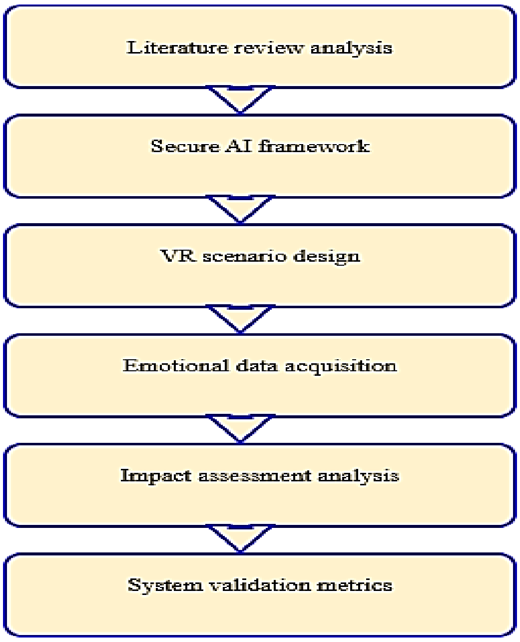


Fig. 7 Major research steps of design and analysis

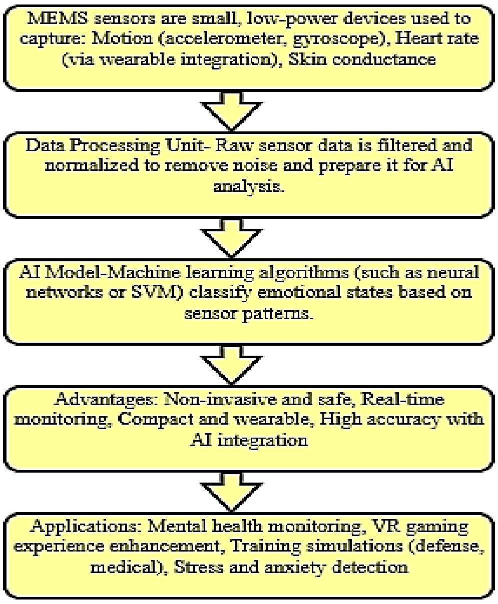
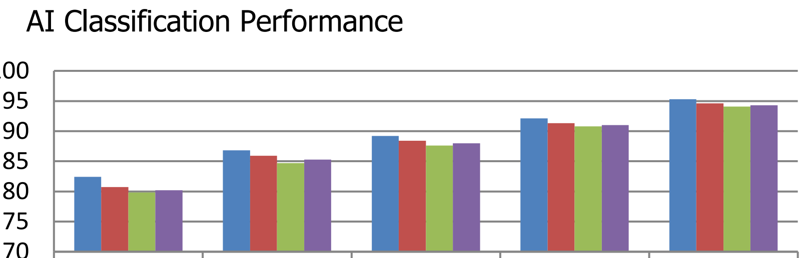


Fig. 8 Overall methodologies and process flow

Thus, by making use of MEMS sensors and AI the entire research is possible[17]. So, in Fig.6, Fig.7 and Fig.8 the major concept and research flow has been shown which has been considered in this paper. Each selected study was evaluated for methodological quality, including study design, sample size, and intervention duration[18]. In addition, the technical characteristics of the VR systems were assessed to determine their suitability and effectiveness for ASD-focused interventions. In figures the major technical process has been shown to provide the overall clarity about the major reason of taking MEMS sensors especially for the detection of motion, skin responses and major heart rate followed by data processing unit for noise removal, next AI models for the identification of emotional states[19]. The entire research has been followed by this order and potential advantages are there like it's non-invasive, accuracy level is high etc. Additionally, it has several applications like mental health monitoring, stress cum anxiety detection etc.

RESULTS AND ANALYSIS

There are several tricks and analysis has been done to understand the concept and explore this research in a good way[20]. In Fig. 9 and Fig. 10 a very clear analysis of AI and overall optimization process has been shown.



	SVM	Random Forest	XGBoost	CNN-LSTM	Proposed AI + Digital Twin
Compare different algorithms: Accuracy (%)	82.4	86.8	89.2	92.1	95.3
Compare different algorithms: Precision (%)	80.7	85.9	88.4	91.3	94.6
Compare different algorithms: Recall (%)	79.8	84.7	87.6	90.8	94.1
Compare different algorithms: F1-Score (%)	80.2	85.3	88	91	94.3

Fig. 9 Overall analysis and performance based on AI classification

- **Experimental Setup:** VR sessions are randomized to prevent anticipation effects, and data collection is adjusted to suit the needs of ASD individuals (e.g., breaks between sessions, lower sensory stimuli if necessary).
- **Machine Learning Model for Emotion Detection:** For emotion detection, we employ machine learning models using a multimodal approach that combines eye-tracking, ECG, GSR based data. Actually, the complex nature of ASD responses, feature engineering emphasizes metrics sensitive to ASD-specific patterns, such as atypical gaze fixation or variable heart rate responses.
- **Evaluation Metrics:** Accuracy and sensitivity are used to evaluate the models, focusing on distinguishing emotional states that are particularly challenging for ASD individuals, such as fear versus anxiety or joy versus calmness. By analyzing these patterns, we aim to understand how VR-based emotion recognition models perform across emotional states, especially those commonly misidentified by ASD individuals.

Initial machine learning experiments indicate that a multimodal approach improves emotion detection accuracy in VR settings, especially for ASD individuals. Preliminary findings show that combining eye-tracking, ECG, and GSR features enables the model to differentiate between high-arousal feelings and low-arousal states (e.g., calmness) with improved sensitivity. Eye-tracking data reveals that ASD individuals often exhibit prolonged fixations in VR environments, possibly reflecting differences in attention. Similarly, ECG and GSR data show that physiological responses to emotional stimuli are less pronounced in ASD participants, which could indicate reduced emotional arousal. This aligns with findings from previous studies that suggest ASD individuals may experience emotions differently, both physiologically and behaviourally. The findings highlight the potential of VR-based emotion recognition to serve as an objective measure for ASD emotional responses. By accurately detecting emotions in real-time, this system could provide immediate feedback in therapeutic settings, helping ASD individuals improve emotional recognition through repeated, controlled VR exposure. Additionally, VR environments could be tailored to support social skills training, with adaptive elements that respond to the user's detected emotional state.

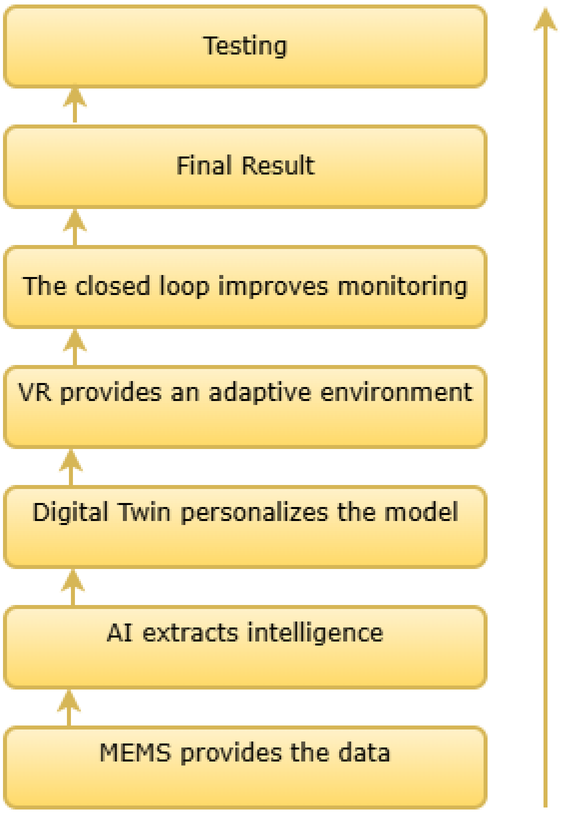


Fig. 10 The major logical research analysis

- **Analysis and Predictive Modelling of ASD:** Ensemble models performed best, with family history and key items identified as the most influential features. These results highlight the potential of machine learning to support early and accurate ASD screening.
- **Dataset Overview:** The dataset consists of survey results from a screening app form. Each entry in the dataset represents a unique individual and contains demographic, medical history, and screening score data. Key attributes in the dataset include:Patient Information: ID, age, gender, ethnicity, relation.
- **Data Analysis and Observations Target Class Distribution:** Approximately 77% of cases are ASD-negative (0), and 23% are ASD-positive (1), indicating a class imbalance. This imbalance requires special handling in model training to avoid bias toward the majority class.
- **Family History of Autism:** Most patients do not have immediate family members with ASD. However, of those who have autistic family members, 62% are ASD-positive, indicating a strong correlation between family history and ASD likelihood.

- **Age Distribution:** The overall average age is 32 years, with ages ranging from 10.9 to 71.1 years. ASD-negative group: Average age is 27.6, with ages ranging from 9.6 to 72.4 years. ASD-positive group: Tends to have a slightly older age Distribution. The different scores show a moderate correlation with the target variable, while A1_Score and A8_Score have a weaker correlation. ASD-negative scores are normally distributed with a mean of around 6, while ASD-positive scores are left-skewed with a mean of 10.5. This pattern confirms that a higher AQ test score correlates with ASD positivity.

- **VR as an Intervention for Social Skill Development:** Here, the diverse Studies report improvements in communication, understanding of social cues, and willingness to engage socially. For instance, children participating in VR programs that simulate social interactions—such as initiating conversations and interpreting body language—showed notable gains in interacting with peers and adults. VR offers a low-stress, controlled environment for practicing social skills, providing advantages over traditional therapy.

- **Emotional and Behavioral Adaptation:** VR has also been found to help children with ASD regulate their emotions and adapt their behavior in response to social cues. Studies utilizing adaptive VR systems, which adjust the difficulty of scenarios based on the child's performance, have shown that these interventions result in improvements in both emotional recognition and regulation. For instance, VR systems can simulate emotional situations, such as an avatar displaying frustration or happiness, allowing children to practice identifying and appropriately responding to these emotions. The immediate feedback provided by these systems helps children better understand the cause-and-effect relationship between their actions and the reactions of others, reinforcing positive behaviors and emotional responses.

- **Limitations in Study Design and Technological Constraints:** While the results are promising, the limitations in study design and technology are evident. Many studies also fail to include control groups, making it difficult to determine whether improvements are truly attributable to VR or are a result of other factors such as natural development or external interventions. Additionally, the technological constraints mentioned earlier, including poor visual resolution and depth perception, still remain barriers to effective VR interventions. Some children experience motion sickness or discomfort, which may limit their ability to fully engage with the virtual environment.

CONCLUSION

Finally, through this research work a novel technique which is primarily based on the concept of Digital twin, AI, VR and MEMS sensors has been provided some unique way of emotional skill enlargement. This work provides very impactful results specially for the mental health as well as related healthcare issues. Additionally, it highlights the potential of VR to enhance societal interaction, sensitive regulation, and adaptability in case of the children those who are with autism spectrum disorder (ASD). VR offers a harmless, controlled environment for practicing real-world skills. However, challenges such as small sample sizes, technical limitations, and short intervention periods limit current evidence. Additional study with larger, diverse samples and longer-term studies is needed to assess VR's effectiveness, scalability, and impact on social and emotional development in ASD for the huge scale healthcare controls. Several analysis have been done and it has been found that there are 65% growth and overall development in the year 2026 which is very high compare to previous few years. Future studies should gather a dedicated VR emotion dataset from ASD participants to enhance model accuracy and relevance. Additionally, investigating other physiological markers, such as EEG or respiration rate, could further improve emotion detection. This report is helpful as a base for expanding VR scenarios to represent a wider range of social situations and healthcare. Apart from that by making use of sensor technology physical models can be implemented with large features.

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