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Review article

Towards next generation digital twin in robotics: Trends, scopes, challenges, and future

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A R T I C L E I N F O

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A B S T R A C T

With the advent of Industry 4.0, several cutting-edge technologies such as cyber-physical systems, digital twins, IoT, robots, big data, cloud computation have emerged. However, how these technologies are interconnected or fused for collaborative and increased functionality is what elevates 4.0 to a grand scale. Among these fusions, the digital twin (DT) in robotics is relatively new but has unrivaled possibilities. In order to move forward with DT-integrated robotics research, a complete evaluation of the literature and the creation of a framework are now required. Given the importance of this research, the paper seeks to explore the trends of DT incorporated robotics in both high and low research saturated robotic domains in order to discover the gap, rising and dying trends, potential scopes, challenges, and viable solutions. Finally, considering the findings, the study proposes a framework based on a hypothesis for the future paradigm of DT incorporated robotics.

1. Introduction

Human civilisation has undergone a shift in technological paradigm with the advent of Industry 4.0. In this new era, where industry, automation and man-machine interaction go hand in hand, a slew of new synergistic fusions of preexisting and novel technologies have been observed to have experienced a staggering rise. Simultaneously, it has also led to the emergence of some new concepts such as Operator 4.0 [1] and Space Factory 4.0 [2,3], where these technological amalgams are seemingly thriving. Apart from the industrial aspect, the research sectors are also being greatly benefited through the use of such technologies. One of the most notable among these fusions is the incorporation of Digital Twins (DT) into various fields of robotics, or more precisely “DT incorporated robotics” as has been addressed in this paper.

On a fundamental level, a Digital Twin of a system or component is the digital replica of the latter that mirrors and or twins [4] the physical component through out its active life-cycle. In other studies “Digital Twin” (DT) has been used erratically to describe various connections between the physical and digital components in the growing volume of literature [5]. The communication infrastructure between the physical and digital components, which is generally unilateral or not taken into account, differs between concepts like

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Nomenclature

AI	artificial intelligence
AMR	autonomous mobile robot
ANN	artificial neural network
AR	augmented reality
ARX	auto-regressive exogenous
ATV	automated transfer vehicle
CNN	convolutional neural network
CSI	confident safety integration
DNN	deep neural network
DTIR	digital twin incorporated robotics
DRL	deep reinforcement learning
DT	digital twin
FFNN	feed-forward neural network
FFT	fast fourier transform
GGS	grasps-generation-and-selection
HCMI	human-computer-machine interaction
HMI	human-machine interface
HRC	human robot collaboration
IIoT	industrial internet of things
IoT	internet of things
ISS	international space station
LbD	learning by demonstration
MBSE	model-based systems engineering
MMI	multi-modal interaction
MR	mixed reality
PCA	principal component analysis
R-CNN	region-based convolutional neural network
RDT	robotic digital twin
ROS	robot operating system
RUL	remaining useful life
RWCS	robot work-cell simulation
SVM	support vector machines
TENG	triboelectric nanogenerator
THT	through hole technology
VTB	virtual test bed
VR	virtual reality
XR	extended reality

the Digital Shadow (DS) and Digital Model (DM) [5]. Glaessgen and Stargel (2012) from NASA provided arguably the most detailed and well-known definition in [6] of digital twin as a multi-physics, multi-scale, probabilistic simulation of a complex system that uses the best available physical models, sensor updates, and so on to replicate the life of its corresponding twin. Several research, however, argued that a one-way connection from a physical system to a digital simulation model could not be termed a digital twin system. Rather, they referred to such a digital replica as a "digital shadow." The articles state that for a digital clone to be termed a digital twin, data transfer between them must be bi-directional [5,7]. Albeit there was a plethora of concepts and definitions for "Digital Twin", no specific definitions were addressed for DT in Robotics or DT Incorporated Robotics. As a result, this research would like to propose an adequate definition of DT Incorporated Robotics as- *"A data or model based digital replica of a robotic system that allows for multi-physics, high-fidelity, multi-scale experimentable simulations through simultaneous and bidirectional state updates over the active life-cycle of the system."* Throughout this paper, the DT Incorporated robotics concept followed the proposed definition.

Ironically, the first digital twin methods which were used in space robotics date back to the 1960s, when the phrase had not even been invented. It was then dubbed "living models" by NASA [8]. Furthermore, the first prime example of DT implementation was observed in 1970 in space robotics. It was used for the historic Apollo 13 mission, which incorporated then cutting-edge robotic technologies used for vital functionalities such as the docking procedure. The mission also marked DT's first triumph in space robotics, as the technology was successfully deployed to safely return the crew from an impending danger caused by the oxygen tank explosion aboard the craft. However, the DT employed back then was a multi-simulator cyber-physical system that largely focused on a physical infrastructure, as opposed to the real-time integration of physical and virtual replicas observed today [8,9]. In 1991, David Gelernter imagined "Mirror Worlds", a similar concept in which software models mimic reality from information input from the physical world [10].

NASA's John Vickers coined the term "digital twin" in 2002. Around the same time, Vickers collaborated with Dr. Michael Grieves to adapt the concept of digital twins as a way to improve product lifecycle management (PLM) in the manufacturing sector. Initially, he referred to it as the "Conceptual Ideal for PLM." Nonetheless, even at this early stage, he mentioned several key properties of digital twins. Grieves discussed the distinction between real and virtual spaces in his paper, emphasizing the importance of data and information exchange between real and virtual entities in order for them to mirror each other [11]. By 2006, his conceptual model had been changed from "Mirrored Spaces Model" to "Information Mirroring Model". In 2010, NASA's draft version of the technological road-map included the term "Digital Twin" (DT) [10].

Since 2003, there had been a surge in interest in the concept of the digital twin. Hyper-automation was named the number one key strategic technology trend for 2020, with digital twins playing a significant role. Initiatives such as Digital Futures and the shift to the Industry 4.0 paradigm are driving this surge in interest. In addition, several key technological advances, such as the Internet of Things (IoT), big data, and real-time sensors, have reduced costs [11]. According to surveys, roughly 75% of organizations implementing IoT projects were already using digital twins. Clearly, the idea is gaining traction, at least among early adopters. According to Markets and Markets, the digital twins market would be worth USD 3.8 billion in 2019. It also forecast a nearly nine-fold increase in market value to USD 35.8 billion by 2025 [11]. Fig. 1 illustrates the progression of Digital Twin over time.

With all of the preceding discussion, it should be abundantly obvious that DT had enormous potential for a wide range of technological domains; however, among all of those domains, this paper sought to determine why and how DTs represent a significant revolution in the interaction between traditional robotic simulation methodologies and the technology that supports them. The answer to the inquiry was discovered in [12] where three major factors were considered. These are -

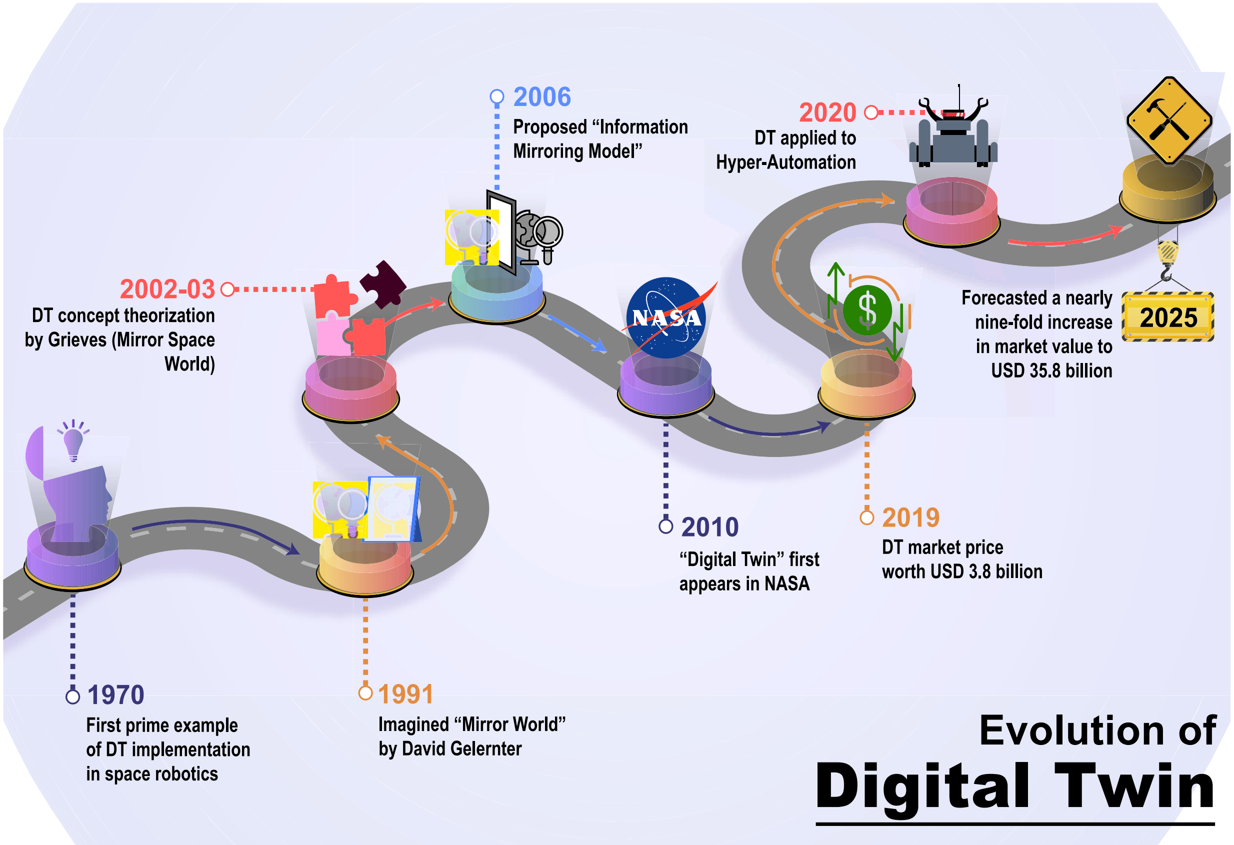


Fig. 1. Evolution of Digital Twin over the years.

a) **Persistence**: A DT is a virtual database of the lifespan of a physical system, such as a robotic manipulator. Individual system information can be recorded on a regular basis, modelled, saved, and maintained across applications. The traditional simulation process, however, is mostly application- specific and need not to store data or mimic the robot for the entirety of its active lifespan. Moreover, by definition the flow of data between a physical system and its DT is bi-directional which provided consistent troubleshooting and predictive analysis feature which are not always in the case of traditional simulation approaches.
b) **Insight**: DTs, like traditional simulation, can be used to forecast what would happen on their physical counterpart. DTs, additionally, give an interface to what is occurring on the hardware right now and a way to investigate the design.
c) **Explainability**: Traditionally, simulations cannot be utilized to offer insight into the interactions of physical systems; instead, precise comprehension of "what-if?" situations is required. When unexpected behaviours emerge, DTs provide a unique perspective for investigating and diagnosing sites of failure. This evidence may be used to enhance process safety, design, and influence future simulations.

System statistics can be retrieved, compared, and analyzed at the same time to better understand and respond to differences between simulation (expectations) and reality (feedback). This is critical in cases when real-time actions are required to prevent dangerous conditions from developing. Well-established, adaptable DTs offer a variety of options to improve collaborative safety in industrial environments, which may be divided into the core areas [12] named Validation, Analysis, Prediction, and Enhancement, which, without a doubt, have unprecedented potential for the manufacturing industry. Consider the instance of a manufacturing-focused industrial robot work-cell. Traditionally, a new robot strategy to be applied would be validated using a simulation framework. Then, for various sorts of analysis such as fault analysis, anomaly detection, and so on, a distinct framework may be necessary. We may use the same simulation framework or AI-aided data analysis frameworks to anticipate the future state based on historical and/or accessible data. Furthermore, more diverse forms of enhancements, such as interactive user interfaces, may need the adoption of a different system. So, typically, an industrial robotic manufacturing facility needs to rely on a number of distinct frameworks that may or may not collaborate, making the whole process more expensive, labor intensive, and time consuming. All of those functions, however, can be combined in a single work-cell with DTs representing the complete plant. Because DTs, by definition, reflect the real system in the digital environment, robot policies may be more precisely developed and then readily transmitted to the physical robot. Again, because DTs are continually in bidirectional contact with their physical counterparts, the analytical data is more precise, allowing for better, easier, and faster diagnosis and predictive analysis. Furthermore, DTs can provide

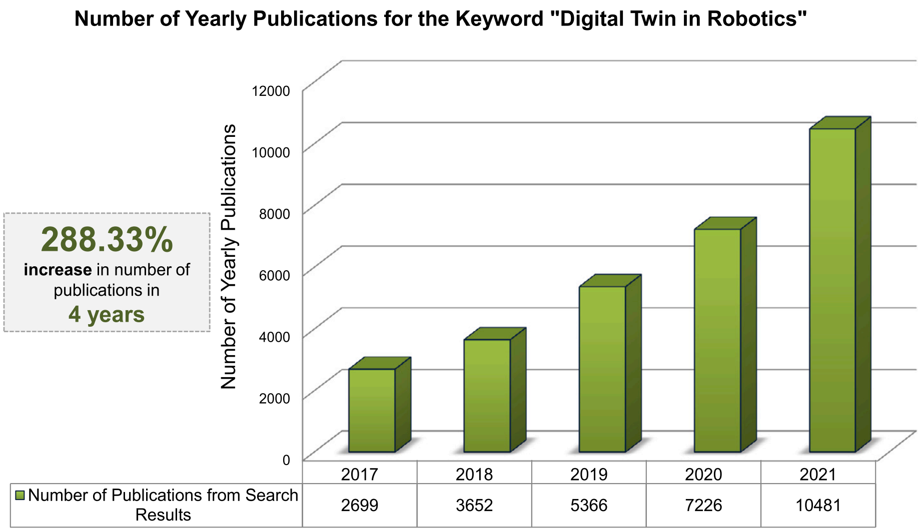


Fig. 2. Number of yearly publications for the keyword "Digital Twin in Robotics from 2017-2021".

an immersive user experience for controlling robots directly from VTBs. This study has gone into much further depth about these technologies in the section 2.

Until recently, DTs were often operated as closed systems that emphasized the expanded capabilities of a single system or robot. As a result, the benefits of broader data access in systems with numerous DTs have been generally overlooked. However, recent emergence of modular frameworks that enable the integration of system-level DTs into a single linked scenario DT (a connected ecosystem of individual DTs) has provided a practical means of seeing these advantages and accessing multi-level data for enhanced process understanding and situational awareness resulting in a surge of research interest in digital twin incorporated robotics. As Fig. 2 depicts, "Digital Twin in Robotics" in recent years has received notable growth as a research interest based on the yearly number of publications obtained from esteemed literature sources such as Google Scholar, IEEE Xplore, PubMed and so on. Such tendency further hints the potential viability of DT incorporated robotics as well as corresponding research opportunities which has been explored in this paper. However, before delving more into this study, it is imperative that some relevant definitions and concepts are discussed.

1.1. Review methodology and contribution of this paper

The methodology adopted in this research comprised a rigorous systematic sampling process of mostly manual sorting of available paper between 2017 and 2022. Prior to 2017, several supporting papers were also necessary to clarify or define a variety of concepts. First, using the keyword "Digital twin in Robotics" numerous esteemed sources of literature such as Google Scholar, IEEE Xplore, PubMed and so on were explored.

The abstracts and metadata of these papers with additional time span restriction aided for first estimation of over 6000 publications. After that, using the Voyant Tool's text analysis feature 617 publications were sorted. Then after an additional 3 layers of manual sorting, 148 publications were finalized for the review process. A schematic representation of the comprehensive review procedure utilized in this article can be found in Fig. 3.

Following the sorting procedure, this study took a unique approach of distinguishing high-saturated DT-robotic domains from low-saturated ones, which was generally lacking in recent review publications, as indicated in Table 1. Based on the domains of robotics covered, the table compares the current study to the most recent review publications that addressed DTIR. It demonstrates how our analysis sheds light on domains of robotics where DT adoption was beneficial but were overlooked by most recent review papers, thus proving the feasibility of our approach. Apart from domain-specific research and trend analysis, this paper has also proposed a framework towards future research trends based on blockchain and metaverse approaches. After a thorough review, this paper has provided some significant contribution towards the present and future state of DT incorporated robotics. The main contributions of this paper are-

i) A novel definition for "DT Incorporated Robotics" satisfying established DT concepts.
ii) A domain-specific research saturation analysis of publication addressing various robotic domains to sort out the disparity illustrated in Fig. 4.
iii) A review of research approaches and trends in highly saturated robotic domains vs. low-saturated robotic domains between 2017 and 2022.
iv) Identification of emerging scopes.

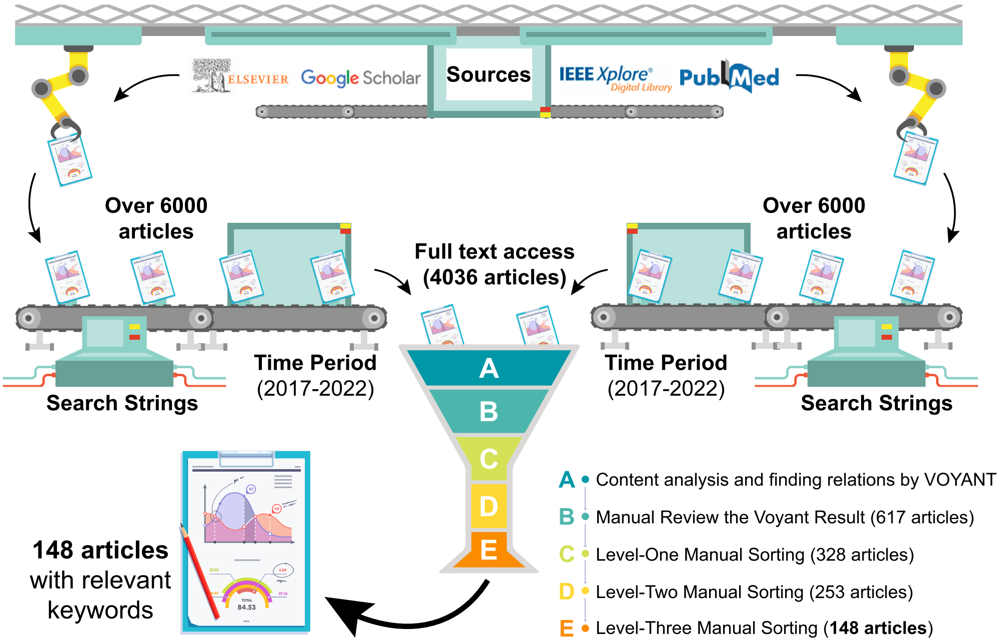


Fig. 3. Publication selection methodology adopted in this paper.

Table 1
A comparison of this paper with recent review articles (PY: Publication Year, DSRSA: Domain-specific research saturation analysis, DT: Digital twin, HRI: Human-robot interaction, IR: Industrial robotics, RM: Robotic manufacturing, SPR: Space robotics, SR: Soft robotics, MR: Medical robotics, RR: Rehabilitation robotics).

Ref.	PY	DSRSA	DT-HRI	DT-IR/DT-RM	DT-SPR	DT-SR	DT-MR/DT-RR
Aivaliotis *et al.* [13]	2019	✗	✗	✓	✗	✗	✗
Lu *et al.* [14]	2020	✗	✓	✓	✗	✗	✗
Lattanziet *et al.* [15]	2021	✗	✓	✓	✗	✗	✗
Phanden *et al.* [16]	2021	✗	✗	✓	✓	✗	✗
Bi *et al.* [17]	2021	✗	✓	✓	✗	✗	✗
Lambrecht *et al.* [18]	2021	✗	✓	✓	✗	✗	✗
Hjorth & Chrysostomou [19]	2022	✗	✓	✗	✗	✗	✗
Fan *et al.* [20]	2022	✗	✓	✗	✗	✗	✗
Ramasubramanian *et al.* [21]	2022	✗	✓	✗	✗	✗	✗
Semeraro *et al.* [22]	2023 [Available Online]	✗	✓	✓	✗	✗	✗
Current Paper	—	✓	✓	✓	✓	✓	✓

v) A hypothesis related to the future DTIR paradigm.
vi) Aggregation of the threats and challenges to implementing DTIR and their proposed and/or provided solutions.

The organization of the paper is as follows. Section 1 provided the introductory concepts related to DT and DT incorporated robotics. In the following pages, section 2 identifies and describes the trends of DT in both high and low-saturated domains of robotics, especially the latter. Section 3 then indicates the emerging areas for future research. Section 4 discusses the existing and potential threats and challenges to integrating DT-integrated robotics, as well as possible solutions. The next section provides one hypothesis for the future DTIR paradigm. Finally, in section 6, the research is summarized and concluded.

2. Recent trends in DT incorporated robotics

Since its very inception in the late 1960s, digital twin and DT in robotics have come a long way in terms of utilisation in domains explored. However, throughout its journey, the technology has been gradually redefined and repurposed from what started as a sophisticated cyber-physical approach in space robotics to modern age, real-time robotic manufacturing ecosystem. According to the substantial research undertaken in this study, five domains of robotics have been evaluated where DT has been found to be significantly implemented. These are -

i) Space Robotics
ii) Medical and Rehabilitation Robotics
iii) Soft Robotics

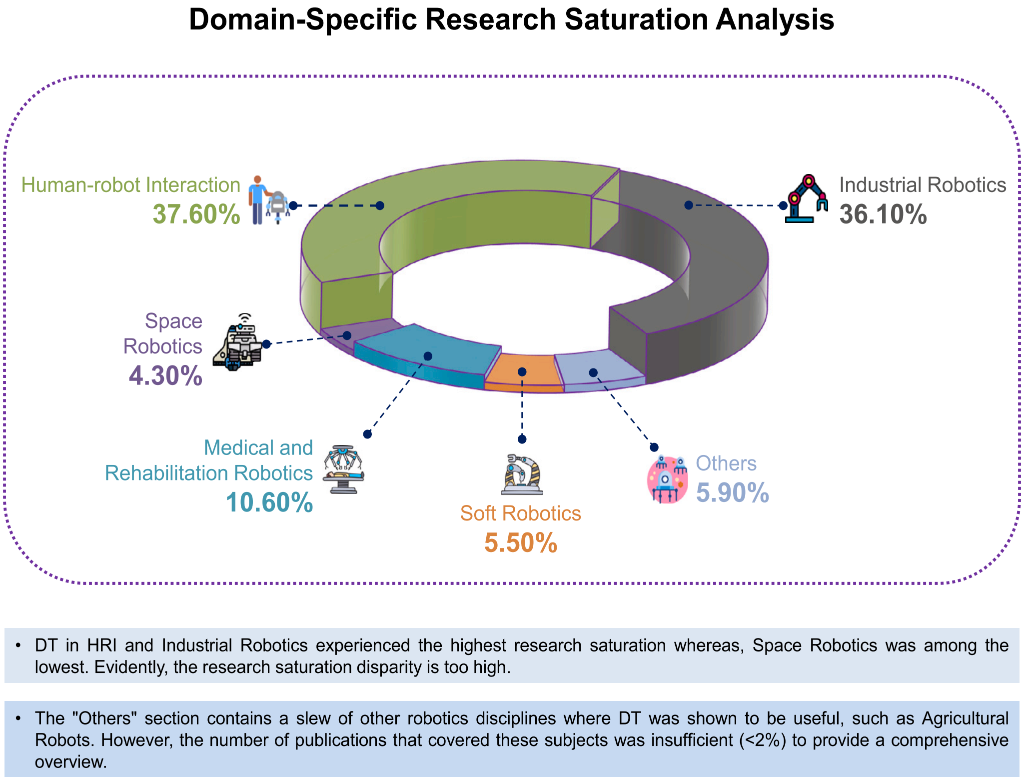


Fig. 4. Domain-specific research saturation analysis.

iv) Human-Robot Interaction
v) Industrial Robotics

Aside from the aforementioned domains, there had been some modest implementations of DT in disciplines of robotics such as agricultural robotics, robots in power generation, and so on. However, the amount and/or impact of papers addressing these fields between the selected time-span was deemed insufficient, thus they were excluded. In this section, the study have intended to provide a comprehensive walk-through of these trends of DT in robotics in the following pages. The low research-saturated domains illustrated in Fig. 4 namely- space robotics, soft-robotics and medical robotics have been heavily described whereas brief elaboration is provided for the high research-saturated domains - industrial robotics and human -robot interaction as an intent to shed light on the domains typically overlooked by contemporary reviews.

2.1. DT in space robotics

The most frequent approaches in DT-space robotics were observed in the case of VTB implementations [23–25]. Other trends included DT- aided haptic telerobotic assembly of modular satellites, processing of such telemetry data [2,3] and spacecraft MRO [26]. Fig. 5 depicts the yearly emergence of these trends, which are further categorized into the following groups:

a) DT Implemented VTBs

In 2017, developed VITOS, a Virtual Testbed (VTB) for optical sensors in space robotics in [23]. In this study, the researchers aimed to incorporate DTs of robots to a VTB where they can be simulated and can be used to simultaneously control the robot actuators. The study imported the optical sensor data such as cameras and laser scanners into the DTs in the VTBs. The data was then used to undertake simulated operations such as the docking procedure of the ATV to the ISS in order to evaluate the method in developing advanced motion tracking and path-planning algorithms that demonstrated prospective outcomes.

In 2018, another study related to a project dubbed “INVIRTES” in [24] conducted an investigation on existing VTBs in MBSE including VITOS [23] where it sorted out that earlier versions of VTBs lacked solid test case specification concepts. The study then went on to propose an integrated model based specification approach for VTBs. The contribution was assessed by deploying the proposed infrastructure on several virtual missions such as in-orbit servicing, Mars exploration, and docking mechanism where it showed promising results in early detection of technical risks. The same year, [25] proposed Experimentable Digital Twins (EDT), a novel simulation-based method that allowed the digital replicas of MBSE systems to be experimentable. The study also proposed a practical approach of implementing such EDT infrastructures into simulation environments dubbed “Virtual Testbeds (VTB)”. According to the study, application of EDT in VTBs brought the former “to life” as VTB provided the run-time environment that

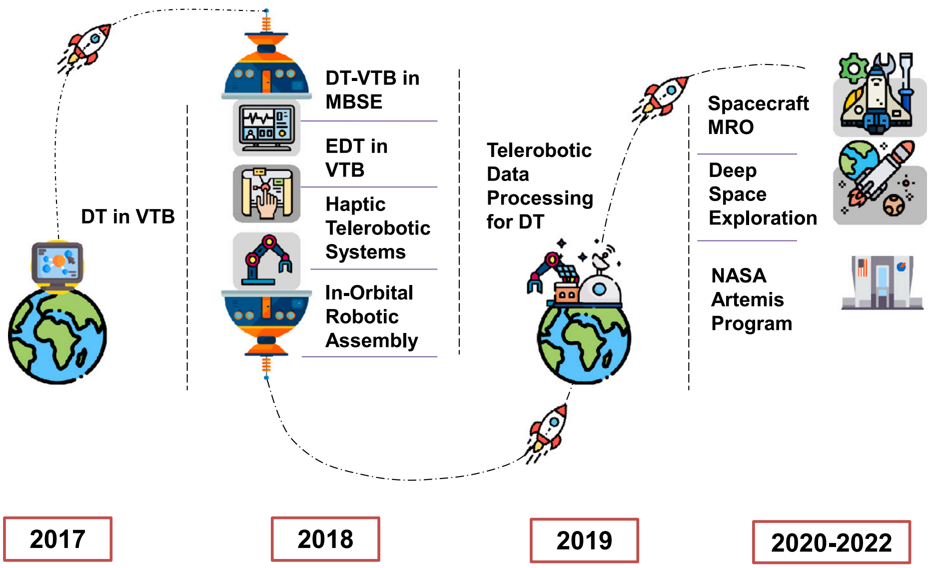


Fig. 5. Yearly appearance of trends of DT in Space Robotics.

makes the EDT more interactive. The study strongly deemed that EDT incorporated VTB had a huge potential in space robotics in terms of developing and testing simulation and component algorithms.

b) DT-oriented Telerobotics, and Modular Satellite Assembly

Several studies focused on the implementation of DT in "Space Factory 4.0", an analogy of "Industry 4.0" to the space domain [2,3]. One study in [2] presented a haptic telerobotic system that employed DT to seamlessly assemble tiny modular satellites in space. The suggested solution favors an HMI that provides direct manual control of robot manipulators via the DT environment contributing to a DT empowered "Space Factory 4.0". Another study in [3] showed approaches for processing the telemetry data of the proposed DT-incorporated telerobotic system in [2].

c) Spacecraft MRO

MRO stands for maintenance, repair and operations. Construction, repair, refurbishment, and maintenance of aerospace elements such as spacecraft bodies and components have been found to be some of the major aspects of DT adoption in modern space robotics. As an example, [26] developed a DT-incorporated robotic grinding system for aerospace MRO (Maintenance, Repair and Overhaul) that utilizes a 6-DoF robotic arm for grinding operations. The automated process uses DT to analyse and identify required grinding variables such the required grinding force.

d) Autonomy and Optimization of Robotic Spacecrafts for Deep Space Exploration

The very first implementation of DT in "Deep Space" exploration was observed in the NASA's 2020 OSIRIS-REx robotic spacecraft. The spacecraft was to investigate Bennu, an asteroid in our solar system with insightful properties. In this mission, the spacecraft employed a substantial number of robotic mechanisms for crucial tasks such as sample collection from the surface of the asteroid, trajectory estimation and maintenance, solar-panel alignment, image and video recording, and so on [27]. The implementation DT was facilitated by Lockheed Martin in a joint expedition with NASA. In the mission the application of DT proved to be a vital decision as it substantially improved mission efficiency by easing complex decision making through evaluated outcomes of simulations run on the DT in a VTB [28].

e) NASA's Artemis Program: A Major Milestone for DT in Space Robotics

Arguably, the next cornerstone in the domain of space robotics and space exploration itself is the NASA's Artemis program. The initiative is supposed to take us back to the moon and set a deep-space gateway which will be further utilized for Mars and outer space exploration. One key aspect of the Artemis program is autonomy at unprecedented levels which is intended to achieve through sophisticated robotic applications and their high-fidelity digital twins [29]. Despite the fact that NASA has yet to release the findings of the conquest, this research considered it worthwhile of mention since it sets a pivotal point for DT in the domain of space robotics.

The emergence of DT was arguably in the domain of space engineering. However, a close inspection suggested that, the trends of DT in space robotics lacked substantial diversification as compared to other domain explored in this paper.

2.2. DT in medical and rehabilitation robotics

Although the concept of medical robotics is not new, its integration with digital twins is, as evident by the considerable absence of publications in medical robotics prior to 2019. This research discovered seven notable trends in between 2019 and 2022 by

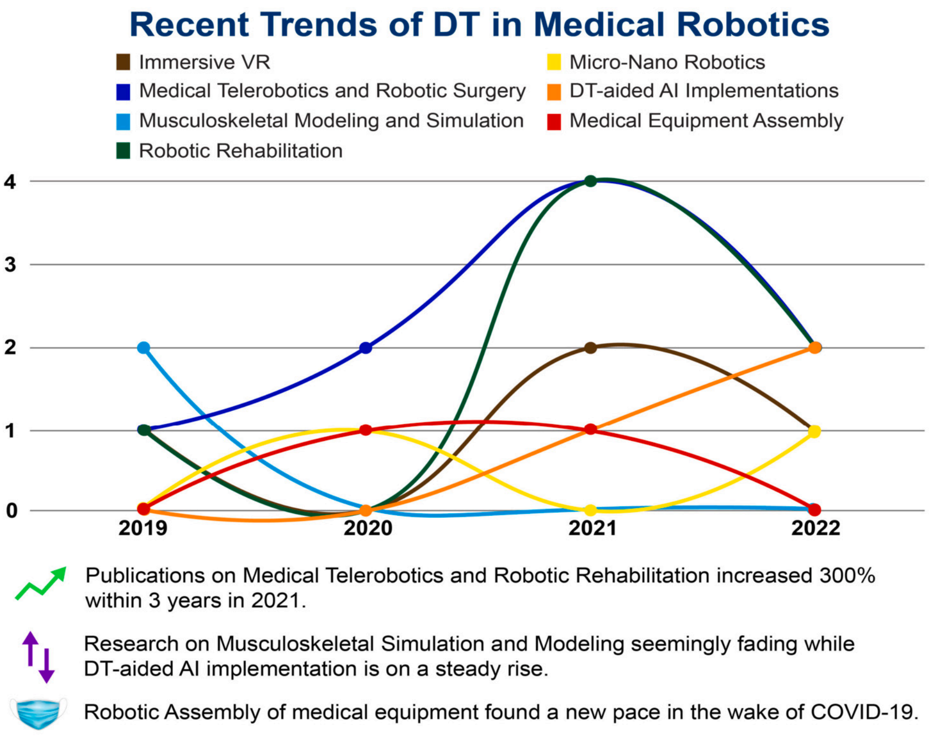


Fig. 6. Recent research trends and applications of DT in Medical Robotics.

conducting a thorough review of existing papers, which can be observed from the line chart in Fig. 6. Considering their frequent interconnection, these trends can be classified into the groups described below.

a) DT-oriented VR, Telerobotics, and Robotic Surgery

As evident from Fig. 6, DT-aided medical telerobotics was one of the fastest growing areas in recent years, with its key applications in robotic surgeries [30–34]. Again, in substantial instances of the medical telerobotic approaches explored in this study utilized an immersive VR interface/environment [30,35,36]. Other use cases included VR assisted telerobotic medical and laboratory equipment management [35], telemedical service robots [37] and RDT-VR assisted e-skin and soft actuator developments for telerobotic bio-sample collection in contagious environments [36]. It could be noted that, the emergence of the COVID-19 pandemic has led to a set of disaster management-centric telerobotic approaches to avoid infections in contagious environments [35,36]. Further details including the approaches relavent to these trends can be found in Table 2.

b) Robotic Rehabilitation and Musculoskeletal Simulation

In recent years, another rapidly increasing trend in medical robotics was robotic rehabilitation, which primarily included development of DT-aided prostheses, exoskeletons and other robot-assisted measures. Sometimes, in order for better compatibility of the proesthesis with its user musculoskeletal modelling and simulations (MMS) were utilized [38]. However, according to Fig. 6, use of MMS in this field was seemingly dying. More detailed description on these trends can be found in Table 3.

c) DT-aided AI Implementation

According to Fig. 6, DT-aided AI implementation was on a steady rise from 2021. In 2021, R-CNN was applied to detect various equipment and their corresponding DTs' positions in a virtual environment [35]. Next year, a DT of a magnetically driven medical micro-bot was developed where non-linear ARX-ANN was utilized to determine system dynamics and predict future outputs in the case of the system [44]. The same year a DT-integrated robot platform was developed that utilized multiple AI methods including U-net, CNN and ASPOCRNet to automatically collect bio-samples from patients' nasal vestibules to prevent spread of COVID-19 among health workers [45].

d) Robotic Assembly of Medical Equipment

Medical equipment assembly by robots gained pace during the COVID-19 pandemic as a measure to counter the staggering rise in medical equipment requirement, especially ventilators. In 2020, DT of a robotic cell was developed for contactless distribution of medicines and other essential supplies in the wake of COVID-19 [46]. Next year, a DT optimized HRC system was developed to deal with the increasing need of medical equipment, especially alternators and medical ventilators. The study demonstrated that by optimizing medical HRC assembly, there was a 25.09% increase in overall efficiency and 20.24% reduction in operator workload. It was also found that before implementing RDT, collision rate was as high as 5.128% which decreased to 0.513% with RDT integration [47].

Table 2
Trends in Medical Robotics: DT-oriented VR, Telerobotics, and Robotic Surgery (PY: Published Year, R-CNN: Region-based Convolutional Neural Network).

PY	Ref.	Approach	Results
2019	Laaki, Miche and Tammi [30]	Haptic telerobotic prototype for robotic surgery as a measure to assess the connectivity and security criteria for implementing DT in a VR environment over 4G network.	Satisfactory latency of 150 ms without any attacks.
2020	Olivas-Alanis *et al.* [31]	A robot-assisted laparoscopic surgery training system where the digital twin of the tools was developed and displayed in the user interface.	Enhanced spatial information.
2021	Hagmann *et al.* [32]	Haptic telerobotic system to aid trainee surgeons in performing minimally invasive surgeries with reduced cognitive burden, in which the Robot-centric DT replicated the robot motions while delivering required semantic information.	60% increase in accuracy for path following, decreased time consumption, and minimal deviation from allocated trajectories.
	Ponomareva *et al.* [35]	A DT-aided VR environment for telerobotic manipulation where R-CNN is used for object detection and spawning their digital representation in the VR environment to compensate for camera limitations such as low-resolution and difficult viewing points.	Decrease in the mental effort of up to 11% and overall effort of up to 16%.
	Shi *et al.* [33]	A DT- aided robotic manipulator for minimally invasive urinary surgeries with synchronous data transmission and control system between the surgical robot and its DT.	30% reduction in average error, 33.3% reduction in maximum error.
	Trobinger *et al.* [37]	A robotic DT architecture where the doctor and the patient are represented by corresponding robot DTs aimed at haptic telerobotic and telemedical applications for elderly people.	More interactive telemedical facility.
2022	Lopomo [34]	Robot-assisted orthopaedic surgery with DT as the visual and analytical interface.	Better assessment of patient-specific scenarios.
	Liu *et al.* [36]	A VR and DT-assisted wearable skin-integrated sensors and haptic robotic soft-actuators for non-contact collection of bio-samples.	Response time: <4 μs (1-5 m distance) Response time: <350 μs (distance <60 m over Wi-Fi)

Table 3
Trends in Medical Robotics: Robotic Rehabilitation and Musculoskeletal Simulation (PY: Published Year).

PY	Ref.	Approach	Results
2019	Pizzolato *et al.* [38]	DT of patients' neuromusculoskeletal and assistive devices for developing patient-specific prostheses.	Likelihood of potential improvements of muscle simulation traits and enhanced patient-specific prosthesis compatibility.
	Feldotto *et al.* [39]	DT-aided musculoskeletal modelling and simulation constructed through CT-scan for biomimetic robot prototype development.	Minimized cost and optimized design, Possibility of muscle dynamics analysis.
2021	Ge, Zhang, Sun and Qing [40]	DT-optimized simulation for robotic hexapod external fixator aimed at bone deformity correction.	Simulated bone deformities were corrected in all cases; Reduced measurement requirement of deformities allowing for reduced scope for artificial error.
	Zhu, Sun, Chen and Lee [41]	Triboelectric sensor-based exoskeletons with DT-optimized interfacing and control.	Minimized latency and response time in both low speed (10 RPM) and high speed (350 RPM).
	Trobinger *et al.* [37]	Haptic exoskeleton for service RDTs	Enhanced feedback
	Topini *et al.* [42]	A haptic hand exoskeleton (HES) for VR based rehabilitation tasks through variable admittance control where a DT of the HES replicates the process in the VR environment.	Better consistency analysis of the HES; Satisfactory admittance response when DT touched virtual objects in VR.
2022	Wang *et al.* [43]	Automatic gait data control system (AGDCS) for self actuating DT-aided lower limb exeskelton.	Successful generation of patient-specific gait and achievement of assigned gait.

e) Micro-nano Medical Robotics

Micro-nano medical robotics was seemingly a new comer as a trend in medical robotics. In most cases, such robot are magnetically driven. In 2020, [48] pointed out important topics such as the characteristics, mechanism and scope of magnetically driven micro-nano robots, where the study mentioned that implementation of DT can greatly optimize such robots for various medical procedures. In 2022, DT of a micro-bot was developed that utilized AI for predicting system outputs [45].

VR assisted robotic surgery, rehabilitative robotics, and DT aided AI deployment appeared to be emerging trends in medical robotics in recent years. Micro-nano medical robotics and robotic medical equipment assembly, on the other hand, appeared to be in their infancy. However, it was clear that the COVID-19 pandemic was a critical catalyst in setting the speed of most DT trends in medical robotics, particularly in the disciplines of medical telerobotics, DT-aided AI, and robotic assembly of medical equipment. However, musculoskeletal modelling and simulation (MMS) may be dying since AI application can lead to appropriate patient-specific prosthesis and modelling as opposed to labor-intensive MMS processes.

2.3. DT in soft robotics

The domain of soft robotics is a relatively new field of robotics that has witnessed some remarkable alterations in recent years, and the use of DT in the field of soft robotics has accelerated this advancement. As experienced by this study, the early implementations of DT in soft robotics focused majorly in VR applications. Later a trend in establishing and developing viable methods and components for sophisticated soft robot manipulator control emerged during 2020. The next phase appeared to be a large-scale integration to HRI and hybrid systems. The most recent trends seemed to focus more on augmented reality integrated application and robot control as evident from Fig. 7. Furthermore, the trends can be aggregated into the following groups-

a) Immersive VR Applications and Reconstruction of Soft Robot DT in VR Space

The most recent research trends of DT in soft robotics aims towards the augmented or extended reality. Apart from establishing effective HRI systems, which will be discussed in the next subsection, virtual and extended reality has exhibited promising results in construction, development and functionality of soft robots in recent years [49,50]. In 2019, [51] proposed that soft robots be used as virtual humans in a human-centered production systems, where the infrastructure's efficiency may be further increased by leveraging DT in VR. As demonstration, the research developed an immersive human-robot simulation is a VR environment using Amazon Sumerian framework where a soft robot digital twin replicated the real-time behaviour of a physical robot. The detection of physical robot movement was primarily done using a depth camera then the detection data were processed and transferred to the digital twin. The research concluded that the unified DT embedded infrastructure exhibited substantial added benefits such as better visualization of robot workspace, better safety assessment and most notably reduction of robot program complexity and process steps.

A critical challenge to presenting the digital replica of a soft robot is the reconstruction of its shape in the virtual space [49]. Albeit there are several approaches to reconstructing DT of soft robots, when it comes to accuracy most of them cannot suffice. As investigated by [49], simple approaches such as single bending angle and curvature parameterizations were inadequate to represent the complex data received by proprioceptive sensor as a full-fledged digital model. Again, ease of understanding being a critical priority in any DT interface restricted representation of DT based on a set of 3D coordinate points as the approach leaded to great difficulty. As described by the research, although there were approaches that mitigated the aforementioned issue and provided ease of interpretation such as the piece-wise constant curvature model, the Cosserat rod model, and the Bézier surface, they once again failed to depict the robot appearance. 3D point clouds, however, had no such limitation except for one that it could not be represented in extended reality. Considering all these trade-offs among accuracy, ease of representation, and integration to extended reality, the study developed an infrastructure based on skeletal animation approach where the soft robot manipulator data was received by embedded colour sensors. Then, the RGBD data fed by the colour sensors was transformed into marker coordinates by FFNN through ROS. Eventually adding additional bone interpolation over these points and rigging the structure, the digital replica was obtained in the Unity platform. In evaluation, the system showed efficient and accurate DT representation with an average of 60 FPS with 16 ms latency.

b) DT-AI Approaches and Utilization of TENG Sensors

One key aspect of any digital twin system is the seamless data transmission between the physical robot and its virtual twin. So far, position sensors and cameras have been utilized to send physical robot data to the digital twin, such as joint positions, contact separation, robot workspace information, and so on. The traditional position sensors have their limits in terms of the increasing connection and collaboration complexity as the system gets more and more complex. So in reality, the employment of cameras, such as depth cameras, is most commonly used in industries for different detection, identification, and workspace defining activities [52].

However, as [53] pointed out, a camera-based digital twin can have several major shortcomings, the most notable of which being its inability to perform in total darkness. It also stated the major complexities of developing a real-time DT with only camera data. Considering such adversities, the study proposed and developed versatile triboelectric nanogenerator sensors suitable for soft robotics that could ensure continuous data stream from physical robot to the digital twin in various adverse work conditions.

The study demonstrated that using such sensors with SVM based data processing leaded to effective perception of 28 objects of varying shapes with 97.1% accuracy which helped the researchers to conceptualize a DT warehouse where camera-based perception was replaced by using TENG sensors.

c) Multi-Modal Interaction

As elaborated in [54], Multi-Modal Interaction (MMI) acted as the activator of the responsiveness of a DT to its corresponding soft robot. The authors pointed out that traditional data processing techniques were inadequate to handle the heterogeneous big data required for establishing MMI for DT. The research put emphasis on advanced ML approaches allied with cutting-edge communication protocols such as 5G to maximize DT-soft robotics and other affiliated systems' efficiency.

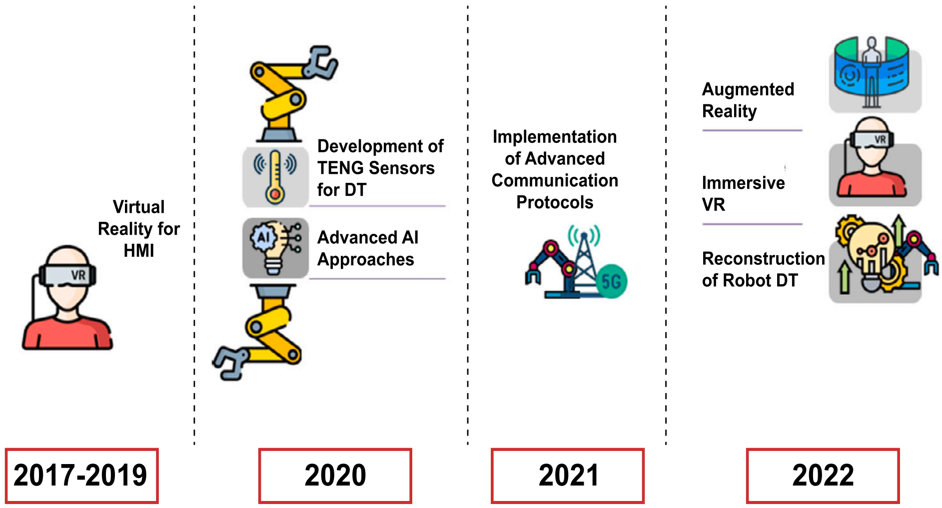


Fig. 7. Yearly appearances of recent trends in DT oriented Soft Robotics.

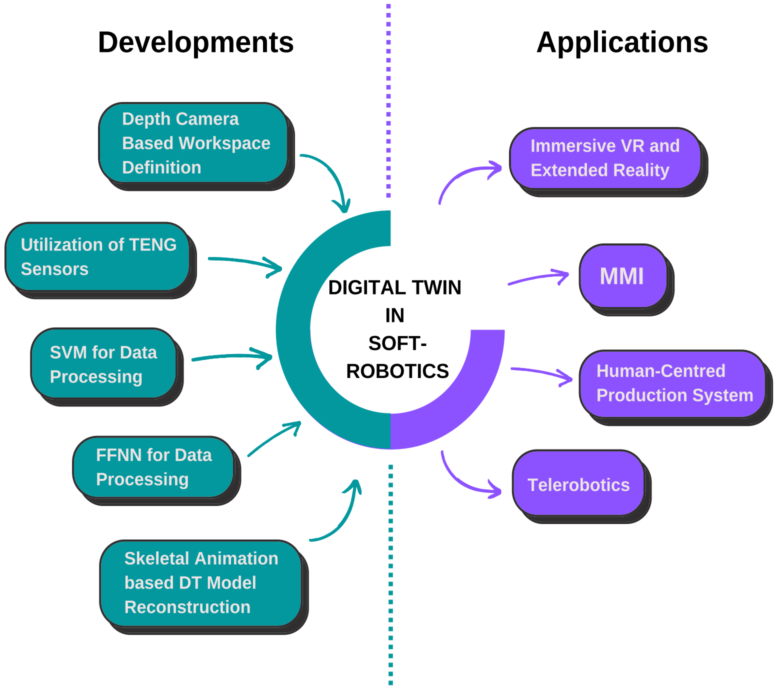


Fig. 8. Developments for and applications of DT oriented Soft Robotics.

It may be argued that the techniques pertinent to the trends covered thus far were either systematic advances of RDT features or applications utilizing DT and soft robotics. Fig. 8 aggregates and categorizes various approaches identified into developments and applications.

2.4. DT in human-robot interaction

As this study observed, DT in Human-Robot interaction exhibited a diverse set of research trends which can be evident from Fig. 9. Despite the fact that many of them include cross-dimensional aspects, the most particular ones had been identified as effective framework creation for efficient DT deployment to HRI, telerobotic applications, MR and VR applications, VTB development, and DT-aided AI implementation.

a) DT-aided MR/VR Applications, VTBs and Telerobotics

DT-aided MR/VR applications achieved the fastest growth as research trends in recent years. Frequently, there had been standalone

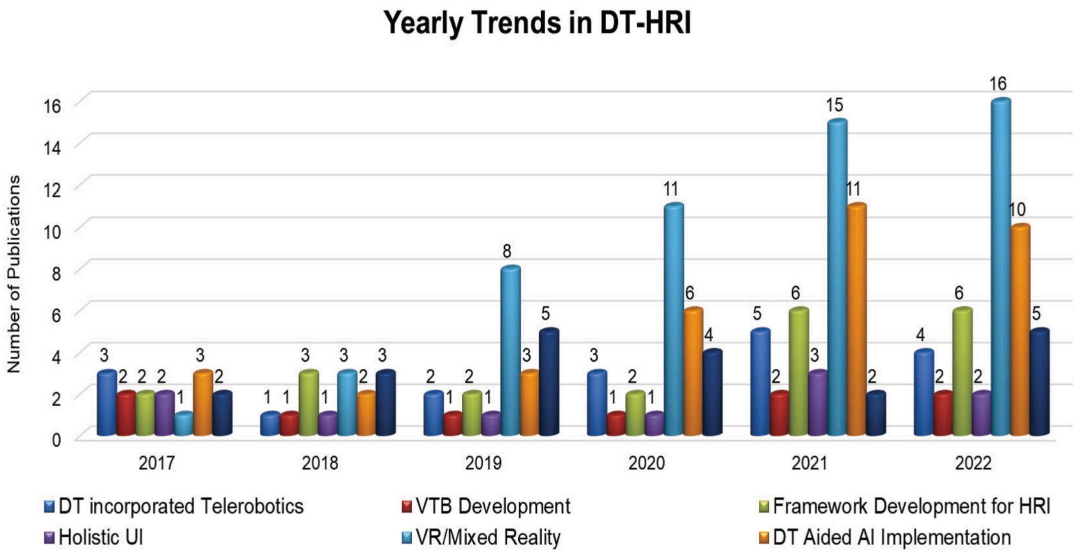


Fig. 9. Recent Trends of DT in HRI.

MR/VR applications between the years 2017 and June, 2022. Early practices aimed to develop reliable and interactive robot control interfaces [55] and affordable 3D reconstruction of DT for robot control in SME factories [56]. Later approaches picked up multi-dimensional interests including DT-aided robot programming in VR and mixed reality (MR) [57–59], warehouse and indoor automation using AMR [60,61], where AMR autonomy is a critical challenge [62], and so on. It was noticeable that, trends in RDT-aided HRI autonomy increased around 2019, especially in the wake of the COVID-19 pandemic [47,61]. Other applications included HRI workspace design and optimization using VR [63], robotic construction supervision in MR [64], and DT-integrated energy-efficient smart manufacturing [65].

Telerobotic applications, on the other hand, took a straightforward approach of controlling robots, especially the ones in industrial robot work-cells [66]. Among the control methods adopted for various telerobotic applications, gesture control had notable appearances [67–71]. One popular way for hand gesture controlled robotic systems was found to be the LeapMotion method [68,72,73] due to its easy implementations in VR space and DT integration. According to [72], DT-integrated telerobotics exhibited promising results in validating developed algorithms and efficient control applications, such as utilizing LeapMotion to operate a Schunk hand through a digital twin in a VTB, which left room for further development with the addition of force feedback. However, as the amount of human-robot workspace multiplied, a key trade-off became apparent. Despite their intrinsic ability to labor indefinitely, robots appear to be incapable of fast adapting to constantly changing work conditions. Humans, on the other hand, despite their remarkable adaptability, cannot work indefinitely [74]. Several studies advocated for HRI systems where the job of adaptation rested on the human operator, who should then operate the robots or cobots correspondingly where DT could play crucial roles [67,74]. One research in particular developed a human-centric DT-incorporated telerobotic workspace where the cobots are controlled by their digital twins by the human operator through various gestures. The robots were made aware to detect collisions with various obstacles such as workplace objects and human operators through real time simulation and processing in a VTB where the robots, the human operator and the interpretation of the workspace were represented through their individual digital twins [67].

In many approaches the versatility of MR/VR interfaces had been utilized to further augment DT-aided telerobotics [35,75–78]. Such augmentations included establishing immersive user interface for robot control [75,77,78], operations in hazardous environments such as nuclear facilities [75] Kinesthetic aid to robot operators [76], AI-based VR data processing for better robot control [35], and so on. Fig. 10 sums up the synergistic integration of DT-aided telerobotics, VR/MR and gesture control for HRI robot control approaches.

b) DT-aided AI Implementations

DT-aided AI implementations picked up significant pace after 2019. Early implementations of AI included robot vision applications [69] where various AI algorithms such as CNN were used to detect real world objects and then export their spatial data to the digital environment. Other early approaches included utilizing reinforcement learning to develop self-learning robots that could learn to lift various weights [79].

More recent studies opted for K-NN, clustering and ANN-based robot trajectory estimation and obstacle detection for safe, collision-free HRI work-spaces [80], FFT–PCA–SVM–VR based DT for human–robot interactive welding and welder behaviour analysis [81], reinforcement learning for developing life-cycle framework and optimizing pick and place robots for virtual product development [82], deep learning based robot development that could self-learn assembly processes [83], DT-aided CNN based human action recognition [84,85], R-CNN based data augmentation for VR assisted tele-manipulation [35], deep learning based eye-gaze and head gesture recognition and data processing for gesture control in robot tele-manipulation [71], reinforcement learning based autonomy of complex assembly workspaces to reduce operator fatigue [86], and many others.

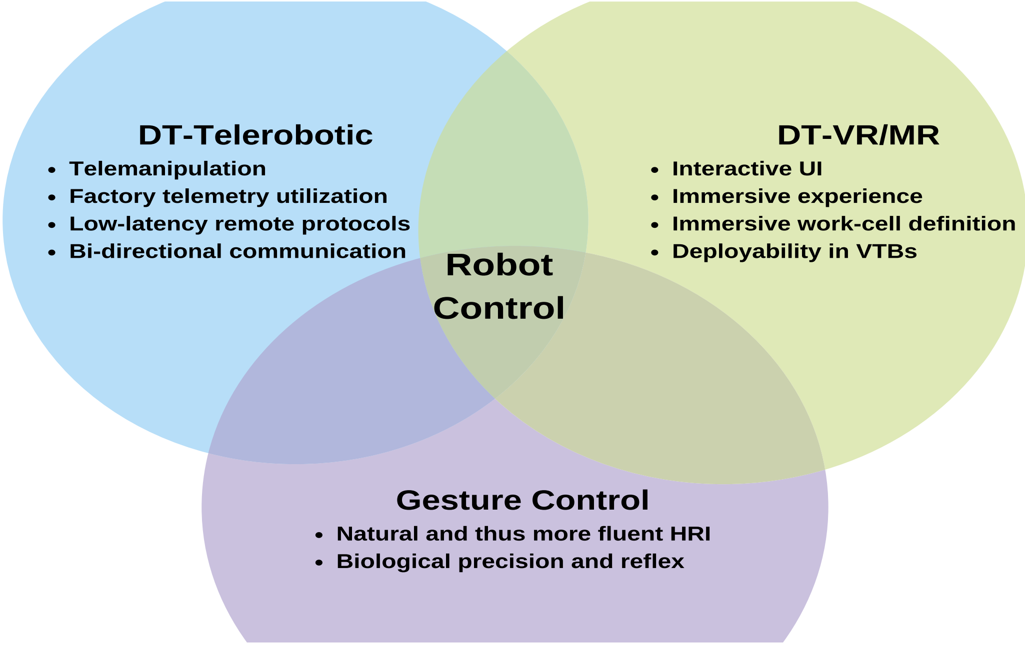


Fig. 10. Synergistic integration of DT-aided telerobotics, VR/MR and gesture control for HRI robot control.

AI-aided RDTs was also effectively utilized to detect human operators and perform corresponding reconfiguration procedures for HRC assembly lines. In [87], a dynamic reconfiguration framework was developed that used AI and ROS to redesign assembly line from data received from 2D and 3D sensors. The results revealed that incorporating DT into the HRI system resulted in a 25% boost in yearly production throughput, an 80% reduction in time required for robot-behaviour redesign, and a 69% reduction in time required for station level redesign.

c) Framework Development

With the advent and meteoric development of HRI integration in modern-day workplaces, a new set of challenges began to call into question the viability of conventional and active organizational structures. As [88] pointed out, modern organizational structures such as Anthony's management control, process standardization, and even HRI/OS failed to perform seamless HRI owing to their reliance on humanistic traits like as interest, rapid adaptability and motivation, which were not directly compatible with robots. As a countermeasure to such concerns, DT-oriented 5C architecture with real-time data exchange had been proposed, in which robots were controlled via their digital twins [88]. Researchers also emphasized the importance of directing digital twins towards achieving MMI and HRI interoperability, which might lead to increased system flexibility, accountability decentralization, and effective supply chain management [89].

d) Other Approaches

Assembly lines on the shop floor were found to provide an optimum space for RDT implementation. In [90], a DT-aided hybrid approach for a dual arm cobot was demonstrated, in which the robot and its environment were replicated in the digital environment via bidirectional sensor updates. Such methodology resulted in efficient and optimized robot trajectories, as well as dynamic and static obstacle avoidance. However, the unified fusion of many sensors and simulator updates was thought to be a very complex process that took a considerable amount of time. Numerous researches alluded that Collaborative robotics had the potential to revolutionise the industrial industry by allowing people and robots to collaborate in shared locations and interact physically to optimize the benefits of both manual and robotic operations. As a result, the market for collaborative robots has grown rapidly in recent years and is expected to reach 5.6 billion USD by 2027, accounting for 30% of the entire robot industry. In reality, however, safety remains a significant concern and a barrier to fully collaborative processes: international standards specify safe operating criteria, but fulfilling them in complex situations is challenging, and there is no guidance on how to build safe collaborative processes.

In 2021, [12] worked on the Confident Safety Integration for Collaborative Robotics (CSI:Cobot) project which was tackling these issues and creating approaches for industrial collaborative robots safety assurance. In recent years, Covid-19 regulations had limited access to physical facilities. So, [75] took an innovative technique by employing digital twins (DTs) and developed a modular, DT framework for broad use. This framework enabled the creation, testing, deployment, and validation of safety technologies both physical and digital. The CSI framework offered a stable environment for iteratively integrating and revising the synthesized safety controller, as well as a virtual test-bed for experimentation. They took advantage of the chance to regularly test and fine-tune the system settings and have provided on their paper a highly modular platform for creating safety-critical digital twins for collaborative robotic procedures. The usage of modular DTs for safety research was a novel contribution of this work. They had also presented their datasets, codes and simulation videos on [75].

Construction robots has grown in popularity in recent years, owing mostly to a movement in thinking toward a more sustainable, recyclable, and carbon-efficient society. Robotic timber construction, which focuses on sustainable design, production, and assembly processes, is one of the top building approaches in this sector. Computer Numerical Control (CNC) technology is used in the robotic manufacturing of timber structures. The automated assembly of wood structures remains a difficult issue, particularly in the construction of highly efficient structures that need specialized design and assembly procedures. Working with non-homogeneous materials, such as wood, poses a number of issues for robotic-driven assembly operations.

The next year in 2022, [91] introduced a new framework for addressing such difficulties in the context of robot-based collaborative construction of wood truss structures linked by unique lap-joint connections that interlock pieces via complicated assembly movements. In the study of [91], they also proposed the idea of Learning by Demonstration (LbD) techniques based on Dynamic Movement Primitives (DMP) to teach robots how to conduct such actions, hence eliminating the need for standard robot programming, which was quite difficult for tasks like this. A digital framework (Digital Twin), design of novel interlocking timber truss joints and robotic LbD assembly method were the main contributions of their work. In this study, they offered a model for using a robotic manipulator to assemble complicated timber trusses. The assembly task could not be efficiently programmed using traditional robot programming approaches. So, they utilized LbD to transfer human assembly abilities to the robotic system. For this method, they designed a teaching robot cell in which the human expert operator teaches the appropriate assembly motions, which were then transmitted to the execution cell. [91] proposed the concept of the assembly digital twin, which directly connected architectural truss and structural design with robotic assembly, which was further strengthened with assembly techniques that use learning by demonstration. The suggested framework's performance was assessed in many trials in which a single human assembly demonstration was performed in various positions in the robot's workspace.

2.5. DT in industrial robotics

The domains of HRI and industrial robotics were found to be so closely woven that the same approaches for HRI were found to be implemented in the industrial domain. However, there were some practices found predominantly in the later domain. As this study experienced, the trends of DT in industrial robotics in recent years can be classified into the following groups-

a) **Robot Work-cell Simulation**
In 2017, a DT integrated five-tier logic operated RWCS was developed in [92] based on the Model-View-View-Model (MVVM) paradigm. It provided successful validation of robot trajectory in complex work-cells. The authors also emphasized on a versatile framework that was compatible to various types of robots and could be applied to different work-cell with great accuracy. A more recent approach in [66] leveraged factory telemetry to develop responsive RWCS in VR and AR where the feedback data is provided by machine vision through cameras. Other RWCS practices included VR-based multi-robot robot work-cell commissioning [93], IKEA virtual robot work-cell [94], and so on.

b) **DT-aided Plant Maintenance**
In [95], following a thorough analysis, it was revealed that DT could be successfully utilized for five types of industrial plant maintenance, including reactive, prescriptive, condition-based, predictive, and preventive maintenance, with the latter two being particularly effective. The approaches were also viable for robot-integrated ones. In 2017 Vachálek *et al.* demonstrated a DT concept which utilized genetic algorithm for DT-optimized predictive analysis and plant augmentation for a robot-assisted production line. The approach was claimed to be successful with 5.2% reduction in overall production time. However, the latency between the DT and its physical counter part was around 1 second which is quite time consuming compared to present day applications which often require latency in millisecond range [96]. Later in [97], a RDT modelling methodology was proposed that used a physics-based approach and virtual sensors to collect and generate an industrial robot data for predictive analysis. The study demonstrated predictive analysis of torque signals from a robot gearbox, with the discrepancy between projected and real data decreasing from more than 2.5 Nm to 0-0.5 Nm after four iterations.
Remaining Useful Life (RUL) prediction was another notable application as a part of RDT-based plant maintenance. As an extension of [97] the authors implemented RUL prediction where it was found that the deviation between real and prediction data exceeded the maximum allowable threshold after 6 months due to mechanical wear [98]. Other contemporary and previous approaches as aggregated by [13] in 2019 were, RUL prediction using time-averaged mode probabilities in a model-based approach, real-time "tail number" composite structure prediction based on measurement and scientific comprehension of fluctuations in multi-physical material attributes, and so on. However, one significant deficiency identified by the authors in the evaluated works was the lack of a common adaptable technique for numerous robots or machines in a manufacturing facility, necessitating specific DT construction for each physical system, which was difficult, costly, and time consuming. In a more recent approach Aivaliotis *et al.* addressed the existing limitations of data-driven predictive analysis, especially its dependency on historical data which was not always available. The authors proposed a novel RUL prediction method based on degradation curves for industrial robots to verify whether or a not a robot would experience failure withing a time-span of 18 months. Results showed that the actuation torque grew with time, as predicted, following the same pattern as the friction coefficient. However, the study considered nominal loading conditions whereas excessive loading was often the cause of mechanical failure of gearboxes [99].
Overall, RDTs in plant maintenance were found to primarily use data-driven physics-based methodologies, particularly for predictive maintenance, which relied heavily on historical data. The introduction of synthetic data generation from digital environments clearly shows great promise, but it is too early to predict whether it will revolutionize plant maintenance because,

in a very complex mixed-body environment, generating digital replicas for each object and then training AI to detect them could be a tedious process.

c) **DT-aided AI Implementations**

In 2017, machine vision was used to generated the feedback data needed to develop a DT of a robot work-cell in VR space [66]. In 2018, reinforcement learning had been applied to aid a robot self learn to lift various weight. The robot model was visualized and could be controlled from its DT [100]. More recent practices included DT-integrated machine vision-based assessment of industrial robotic skills [101], and industrial robot programming using machine learning enhanced point cloud information and RDT [102]. A critical shortcoming of data-driven RDT approach as hinted by [99] was lack of historical data. However, this limitation could be resolved through generation of synthetic data the accuracy of which could be further enhanced by AI algorithms. In [103] the authors demonstrated a CNN-based approach to generate additional synthetic image data from digital models which exhibited a success rate of 100% when the developed model was retrained and used to detect real world objects in different orientations.

Advanced AI methods had also been used for effective fault diagnosis for RDT-assisted manufacturing. In [104], the research demonstrated a novel technique for fault diagnosis using deep transfer learning. The results showed that the proposed deep transfer learning aided fault diagnosis achieved an accuracy of 97.96% surpassing the then state-of-the-art DNN approaches.

Developing efficient AI algorithms for physical robots is a critical challenge due to its excessive time consumption, power supply and component limitations for long-term repetitive motions, lack of appropriate VTBs, and so on. An effective solution to this issue is to develop the algorithms through extensive simulations where DT was observed to play viable roles [105,106]. Examples included a DT-aided DRL-based policy transfer from simulation to physical robots [105], and training robots in their DTs for intelligent robot grasping applying grasps-generation-and-selection convolutional neural network (GGS-CNN) with 96.7% and 93.8% success rates for gripping single items and mixed objects, respectively [106].

d) **Industrial Cloud and Edge Robotics**

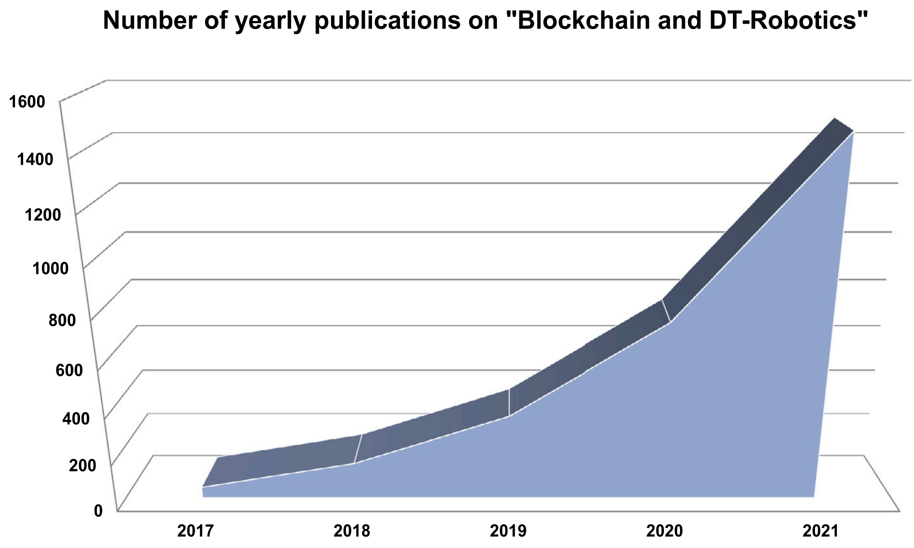
Cloud and edge robotics - both are relatively new aspects of the industry 4.0 paradigm. Implementation of various IoT and IIoT technologies as middlewares [107] took these to the vastly interconnected shape they possess today. A DT-aided cloud-based robotic manufacturing system was developed to assemble different THT-Devices on a PCB [108]. However, [109] pointed out that, while cloud robotics held promise owing to greater processing capabilities and cost minimization, it was vulnerable to real-time response and security due to its centralized form. Instead, the study chose edge robotics to improve responsiveness, encourage decentralization, and optimize bandwidth. The proposed architecture was tested using two DT integrated robots, and coordination was improved further by providing the robots radio information. When it comes to latency, edge computing has an inherent advantage over cloud computing being faster [110], which allows it for an effective method for real time fault diagnosis. As demonstrated in [111], edge-based networking could be effectively utilized with ROS analysis stack for fast and real time fault detection and anomaly diagnosis.

e) **Blockchain in Industrial RDT**

Very recently implementation of blockchain technology in RDT applications had been gaining noticeable traction owing to it security and traceability. In [112], the authors developed a Blockchain integrated RDT for a construction robot to build a mock-up bridge using prefab bricks. The findings revealed that the technique was easily traceable because the RDT data was stored on the blockchain with associated timestamps. Furthermore, the study found that according to consensus technique, the methodology was more secure since it prevented hacked or corrupted data from being exposed to other nodes in the system, resulting in total immutability. However, it was mentioned that large amounts of data could be transferred withing 3.42 seconds. Collaboration of DT and Blockchain had been proposed to augment industrial internet for industrial applications including robot-assisted smart manufacturing in [113] which showed smart collaboration between industrial robots, DTs, edge devices and others where blockchain aided in immutable data transmission.

One major shortcoming of traditional blockchain was its processing delay which could be fatal for RDT applications requiring latency below millisecond range. Khan *et al.* addressed the issue and proposed an alternative blockchain framework dubbed twinchain for DTs which was merged with a six-dimension spiral DT architecture. As a proof of concept, the study experimented to produce a robot surgical machine where the performance requirements could be stored in the twinchain. The suggested architecture, according to the study, produced a significant decrease in transaction time when compared to regular blockchain [114]. However, no quantifiable performance indicators were supplied to measure the amount to which performance was enhanced. In [115], the authors tackled the delay problem as well, demonstrating a novel algorithm for sample rate selection and discriminating between time-sensitive and time-insensitive data, with the former being favored. The research claimed to have successfully transferred industrial DT data securely at a much faster transmission speed than typical blockchain networks by merging cloud computing with big digital twin data (BDDT). In a very recent study, the researchers introduced FedTwin a novel technique for adaptive asynchronous federated learning of industrial digital twin networks enabled by blockchain that employed Proof-of-Federalism (PoF) resulting in autonomous digital twin networks. Furthermore, the method utilized Generative Adversarial Network (GAN) to improve the security of the method to prevent corrupted DT data from being shared [116]. So in a nutshell, the current focus of blockchain enabled industrial RDTs are centered more around reducing the delay time which is critical for time-sensitive RDT applications.

During the literature study and trend analysis, a plethora of research trends, applications, and matching technologies were uncovered. The aggregate of the core approaches is shown in Table 4. It was also revealed that there were various constraints and



	2017	2018	2019	2020	2021
Number of Publications	48	155	362	753	1480

Fig. 11. Number of yearly publications on “Block-chain and DT-Robotics”.

difficulties to implementing DTIR in the chosen robotics fields. Table 5 presents a brief description of these identified and detected limits and problems.

3. Research scopes in DT incorporated robotics

As previously mentioned, the DT paradigm will soon dominate robotics research. Consequently, the areas of research in this discipline are expanding quickly. While certain trends are beginning to fade, others are becoming quite popular in the respective areas. An existing trend either fades or is augmented when new, faster technology is incorporated, is economically viable, and is well integrated into the system. In this section, the potential research scopes have identified as the trends that were found to be emerging or at least consistent. The scopes and why they are growing have also been discussed as well as the limitations and/or challenges that come with it. Throughout the domains explored, it can be observed that mixed reality and VR applications, haptic telerobotic applications, DT-integrated AI implementations, robot work-cell simulation are the most emerging trends. Further discussion on these trends ensues below for greater understanding.

a) Immersive VR, MR, AR and XR Applications

Immersive VR and mixer reality applications have been found dominant in every single domain explored in this review. Especially, in the case of DT-HRI, DT-IR and DT- soft robotics, this trend is growing rapidly. According to various studies, the reason for this staggering growth lied beneath the inherent ability VR spaces to provide an immersive experience that can integrate better workspace visualization features, interactive holistic UIs, ability to control robots from VR space, and so on [57–59]. In short, it can provide a user-friendly all- in-one place control and visualization interface for RDTs.

However, construction of RDT model, especially for soft robots and exporting that to the VR space was found to be quite a tedious task [49]. Again, as it was discussed in [53] RDTs based on traditional optical sensors are limited to presence of light, which leaves room for further research opportunities to overcome such limitations.

b) Smart Manufacturing through Robot Work-cell Simulation and RDT-based Plant Maintenance

Robot work-cell simulation and RDT-aided plant maintenance, especially the latter were among the most consistent and growing trends in the domain of industrial robotics. As this study experienced, implementing DT with RWCS, augments real-time visualization, analysis, control and evaluation of robot work-cells. It also made it possible to apply advanced AI approaches to verify robot actions prior to practical implementation [92].

On the other hand, predictive maintenance had been found to be substantially promising trend of RDT. The ability of RDT to predict future performance and states of robot components [96,97] with the added benefits of RUL prediction [13,97,98] was found to do wonders in plant maintenance.

However, as observed by this study, with a RDT actively in a bidirectional contact state with its physical throughout its lifetime collecting data, the process becomes computationally intensive. Also, in such a simple bidirectional state, there could be openings for data breaches. Latency is another critical concern, especially in HRI work-spaces where safety is a fundamental concern. To many extents, the security issues were found to be resolved by blockchain implementation as in [112,113]. According to Fig. 11, research interests in blockchain and DT-robotics has achieved a staggering 2983.33% increase in just 4 years clearly hinting the viability of

Table 4
Summary of core research trends and applications covered in five major domains of robotics.

Research Trends/Applications of DT Covered in Five Selected Domains of Robotics				
Space Robotics	Soft Robotics	Medical & Rehabilitation Robotics	Human-Robot Interface	Industrial Robotics
• Motion Tracking & Path planning in VTBs.	• Robot control and condition monitoring from immersive VR/MR/AR/XR.	• Haptic telerobotic surgery.	• VR/MR-aided interactive robot control interface.	• Policy transfer from RDT to physical robot.
• Integrated model-based specifications for VTBs	• Construction and state update of RDT in VR space.	• Laparoscopic robotic surgery training system.	• 3D reconstruction of RDT for robot control.	• Robotic work-cell simulation.
• Experimental Digital Twin (EDT) in VTB.	• Utilization of TENG sensors to overcome camera-based feedback limitations.	• R-CNN aided telerobotic manipulation from RDT.	• Robot programming in VR and MR.	• Robot condition monitoring in VR and MR.
• In-orbital modular satellite assembly.	• FFNN-assisted RDT state update from RGBD data and bone interpolation method.	• Contactless robotic distribution of medical supplies in COVID-19.	• Warehouse and indoor automation using AMR.	• Robot trajectory validation.
• Telemetry data processing for space factory 4.0.	• SVM-based RDT RDT data processing.	• System dynamics estimation of magnetically driven micro-bots assisted by ARX-ANN.	• Energy-efficient smart manufacturing.	• Predictive maintenance through AI and degradation curve analysis.
• RDT assisted spacecraft MRO.	• Multi-modal interaction.	• Neuromusculoskeletal simulation for patient-specific prosthesis development.	• Telemanipulation using Leap-motion controller.	• RUL prediction.
• Trajectory optimization and task maintenance of robotic spacecraft, OSIRIS-REx.	• Telemanipulation of soft robots from DT.	• Biomimetic robot development.	• Robot algorithm development and assessment.	• Fault and anomaly diagnosis.
• NASA Artemis program.		• Robotic fixator optimization for bone deformity correction.	• Eye-gaze and gesture-controlled telemanipulation.	• Synthetic data generation for data-driven RDTs.
		• Triboelectric sensor-based exoskeleton development.	• Collision detection and obstacle avoidance for cobots.	• Cloud-based assembly of THT devices on PCBs.
		• Haptic exoskeleton for VR-based rehabilitation tasks.	• Cobot trajectory optimization.	• Blockchain and Twinchain-aided smart robotic manufacturing.
		• Automatic gait data control for lower limb exoskeleton.	• CNN-based object detection and sync of object data between system and DT.	• Cloud-merged GAN-assisted adaptive asynchronous federated learning for industrial RDTs.
		• Telemedical interaction between patient and doctor using RDT agents.	• DRL-based robot self-learning.	
		• Non-contact collection of bio-samples.	• FFT-PCA-SVM-VR- aided robotic welding.	
		• R-CNN aided medical equipment detection and spatial data transfer to virtual space.	• Human action recognition for workspace safety.	
			• Human action recognition for workspace safety.	
			• R-CNN based RDT data augmentation.	
			• Organization framework assessment and development for DT-HRI.	
			• Transfer of human assembly capabilities to cobots.	

Table 5
Summary of domain-specific limitations/challenges detected.

Domain-specific Key Limitations/ Challenges Detected				
Space Robotics	Soft Robotics	Medical & Rehabilitation Robotics	Human-Robot Interface	Industrial Robotics
• High Latency. • Deviation of VTB environment from target space. • Performance reduction of optical sensors in darkness.	• Model complexity of soft robots. • Construction of soft robot DT. • Inability of camera-based feedback to work in complete darkness.	• Highly sensitive accuracy and precision requirements of manipulators used in robotic surgery. • Critical latency requirements, System complexity. • Limitations of RGB sensors for medical equipment detection and data transmission in low-light conditions.	• Accuracy and precision maintenance. • Safety assurance of human operators. • Low latency maintenance. • Computationally intensive modelling and simulation. • Incompatibility with existing organizational models.	• Accuracy and precision maintenance. • Network safety from cyber-threats. • Processing delay of Blockchain-enabled industrial networks. • Computationally-intensive modelling and simulation. • Data immutability assurance.

blockchain in RDT applications. There were two major aspects to which this research deemed blockchain to be the next generation DT and thus DT incorporated robotics optimizer, which are -

i) **Decentralization**
The decentralized nature of any blockchain network is its defining feature. The process control is divided across several controlling devices known as nodes in such a network. As a result, by using this blockchain characteristic, smooth DT-integrated robotic applications can be constructed in which the robotic process may continue even if a controlling device fails as long as at least one node is functioning.

ii) **Security**
Blockchains, according to IBM, are more secure. In comparison to traditional networks, the multi-node control in the decentralized structure makes it extremely difficult to breach all of the controlling devices, and the system may be restored as long as at least one node is safe. Second, in a blockchain network, smart contracts, transaction data, and the cryptographic chain of blocks are tightly encrypted, making successful breaches unlikely [117]. So, a blockchain powered RDT is more likely to be more secure than RDTs powered by traditional networks.

but again, blockchain networks were still found to be working above the millisecond response time ideally required by RDT systems [114]. Thus, there significant scope for research opportunities to augment plant maintenance security and processing speed by optimizing blockchain networks.

c) Haptic Telerobotic Applications

Apart from MR and VR, Haptic telerobotics in another trend that had been found emerging in almost every domain. Especially, in the domain of medical robotics, it was found to growing at exceptional rate due to the increasing research on remote robotic surgeries. On the other hand, the trend had picked up a boost due to the emergence of the COVID-19 pandemic as an attempt to establish contactless assembly and manufacturing to prevent spread of the disease [35,36,47]. The addition of haptic feedback [36] and various gesture control methods, such as leap-motion control [72] was found to have the ability to combine biological reflex to telerobotic precision. However, as observed by this study like in other RDT applications, latency and medium noise are two critical challenges to overcome to ensure seamless telemanipulation, which require for further research.

d) DT-Aided AI Implementations

DT-aided AI implementation had been growing consistently in most domains to achieve autonomy through machine vision [66], robot self learning [100], intelligent and autonomous data processing [104]. Especially, methods such as robot policy transfer [105, 106] and CNN [103] had been observed to be thriving in domains such as human-robot interaction and industrial robotics. Such additions had led to many intelligent solutions to boost production, ensure better safety at HRI work spaces, reduce collisions and thus increasing plat efficiency. AI augmented machine vision had been utilized as an effective tool for fast immersive DT environment creating and VTB development by providing spatial data. In many cases, AI approaches had been found to augment RDT data to minimize human error. Therefore, more research can lead to potential developments through DT-aided AI implementations.

Despite the revolutionary contributions of AI in these fields, in many aspects these algorithms are too computationally intensive to be implemented into embedded devices resulting in increased hardware cost and processing power requirement. Thus, there are great opportunities for further research in developing light, fast and effective AI models.

4. Threats, challenges and possible alternatives

While incorporating DT into numerous sectors of robotics may result in extraordinary advancements, its implementation is a significant challenge. Aside from its introduction as a new technology in Industry 4.0, which may be referred to as the tip of the

Table 6
Challenges of framework incompatibility with different organizational models.

Models	Concept	Challenges
Agile and lean management [118]	Task collaboration based on informal and direct communication.	Establishing a skill-specific and flexible decision-making process.
Management control of Anthony [119]	One moderator for task assignment.	Leadership assignment and acceptance of robot supervision over human operators.
Process Standardization [120]	Tasks and processes follow specifications.	Error management.
Meta-organization of Ahrne and Brunsson [121]	Result specification independent of which tasks requires to be accomplished.	Communication and collaboration complexities.
Missionary [122]	Provides purpose.	Ineffective for robots.
Professional bureaucracy [122]	Knowledge and skills are standardized and applied to tasks.	Adequate task identification and match-making process.

iceberg, the technique may be subjected to a variety of present and prospective threats and challenges. This study defined “threats” as factors that may directly compromise the integrity of RDTs, and “challenges” as circumstances that may prevent RDTs from attaining their full potential. In both cases, several alternatives were investigated and proposed as summarized in Table 7. The following pages encapsulate the complete context.

a) Framework Incompatibility with Existing Organizational Frameworks

Apparently, as [88] pointed out, most existing organizational models possessed varying compatibility issues with DT-HRI implementations leading to corresponding challenges. As a solution, the author recommended not relying on a particular organizational model. A proper summary of different organization structures is represented in Table 6.

b) Generic Framework Model or Architecture

It was a possible gap that impedes the expansion of DT across diverse applications for the development and implementation of DT. There were no plug-and-play modules available to develop a DT thus a RDT for any given system at the moment. An AutomationML-based plug and simulate idea demonstrated the automated configuration of the virtual environment through the transmission of XML data from the plant simulation environment. In this case, the modular DT interacted with the real-world setup to link and transfer data, therefore assisting in decision-making [21,123].

c) Lack of Structured Training Programs

The lack of structured RDT training programs resulted in a gap in engineers’ and developers’ skills and expertise. As a result, a lack of relevant information might result in time, energy, and resource losses while constructing a DT model. As a result, appropriate training and multiple application models were required to prepare designers and engineers to construct the DT model. To do this, engineers could be trained and given hands-on experience with RDT during their undergraduate studies. University programs could encourage the use of digital tools wherever possible and increase computer science education in engineering courses, as long as this does not come at the expense of a diminished emphasis on conventional, core coursework. The difficulty here was to balance foundational engineering courses with the inclusion of DT computer science related topics to the curriculum. In light of this possible issue, strategies for reorganizing courses in engineering schools could be implemented. One approach would be to include elective courses in robotics and DT technologies [21].

d) High Development Expenses

The creation and modelling of the DT model necessitated financial, plant downtime, and man-hour investments in order to adopt and deploy DT at multiple system levels and integrating sophisticated DT frameworks to robots increased the difficulty several notches. Furthermore, there were several uncertainties associated in developing the system model, real-time feedback, and interaction between physical and virtual models. The multitude of alternative stated that the DT-HRC could assume at any one time, given the dynamic nature of the human working with the robot, was also a barrier to employing the DT-HRC for process improvement. The enormous number of characteristics that influence these sorts of interactions expanded the number of conceivable system states. Thousands of external and intrinsic elements could influence the HRC situation. Finding all of these characteristics and reproducing the identical conditions in the virtual world would be time-consuming. Similarly, purchasing and using commercial process simulation software with the necessary toolbox or plugins to create a DT was also costly. As there was still a lack of awareness and knowledge regarding DT concepts, it was more difficult for the manufacturing industry to implement DT concepts. To overcome this type of issues, it was very important to increase the awareness and knowledge of DT. By creating more and more knowledge on it, it could be the potential solution for the cost of development on DT [21].

e) Low Accuracy and the Precision of the DT Simulation Model

Most DT models generated a virtual copy of a robot by capturing its motion in the real world and replicating it in the virtual world. To find the best parameters for optimal results, DT provided the ability to implement various algorithms that could run in parallel without affecting the real-world setup. Most of these, however, failed to consider the modelling of various complex processes within a DT model, such as gripper finger wear and tear, servo gear wear, the effect of latency between the gripper and the controller, and the repeatability of the robot over time [21]. As solutions to these challenges, this paper would like to propose using AI-aided modelling for accurate digital model generation. For higher precision, AI can also be used to augment the traditionally implemented

Table 7
Summary of detected threats and challenges and their possible solutions.

Serial No.	Threats/Challenges	Provided/Proposed Solutions
01	Framework Incompatibility with Existing Organizational Framework	Using a mix of multiple organizational models [88].
02	Generic Framework Model or Architecture	Automated configuration of the virtual environment through data transmission from the plant simulation environment [21,123].
03	Lack of structured RDT training programs	i) Training engineers and technicians to provide them with hands-on experience with RDT. ii) Including elective courses in robotics and DT technologies [21].
04	High development expenses	i) Increasing the awareness and knowledge of DT to reduce misuse [21]. ii) Development of less computationally intensive RDT frameworks to reduce hardware and processing cost.
05	Accuracy and the Precision of the RDT Simulation Model	i) AI-aided modelling for accurate digital model generation. ii) AI-augmented traditional controllers such as PID, Fuzzy logic, and so on. iii) Using edge computation over cloud computation for time-critical RDTs.
06	Cyber Threats and Computational Limitations	i) Implementation of common solutions such as Secure Socket Layer (SSL), IPSec, cryptographic algorithms, intrusion detection, and prevention systems, and digital certificates [124]. ii) Development of less computationally intensive RDT frameworks to reduce hardware and processing cost.
07	Network Connectivity Issues	i) Reducing the high fault tolerance, lower latency, implementing hyper-connectivity, lower ping and increasing the coverage by developing the network connectivity of the system [125]. ii) Using edge computing instead of cloud computing for time-critical RDT applications.

controllers such as PID, Fuzzy Logic and so on. To reduce latency for time-critical applications, it is recommended to utilize edge devices instead of cloud computation provided that the systems are compatible.

f) Cyber Threats and Computational Limitations

Cyber threats were among the most common threats for RDTs and DTs in general. According to [126], what an individual was aware of regarding events (e.g., issues, attack attempts) that occurred in the cyber domain was referred to as cyber situational awareness (e.g., industrial networks). There was also some survey on cyber physical threats in [127]. The cloud computing faced the same challenges as traditional IT solutions [124], such as denial of service (DoS), Man-In-The-Middle (MITM), eavesdropping, IP-spoofing, and masquerading attacks. Traditionally, these issues had been addressed through the implementation of common solutions such as Secure Socket Layer (SSL), IPSec, cryptographic algorithms, intrusion detection and prevention systems, and digital certificates [124]. On the other hand, there were some the computational limitations that devices present with their low-speed processors, memory, and energy limitations were among the challenges that IoT presents for a secure healthcare networked environment [124].

g) Network Connectivity Issues

Network connectivity issues such as latency, high ping, coverage issues etc. all were the great challenges for RDTs and DTs. In [128], authors discussed about the market challenges of the 5G network with some open questions that effect the digital twin technology. On the other hand, P2P, P2V and V2V were some required communication systems where connectivity and latency issues would arise, and those were represented in [125]. The solution for this kind of challenge could be reducing the high fault tolerance, lower latency, implementing hyper connectivity, lower ping and increasing the coverage by developing the network connectivity of the system. The requirements for P2P and P2V communications were - profound network structure, low latency, and hyper-connectivity. Whereas the requirements for V2V communications were - information reliability and high fault tolerance, low latency, and hyper-connectivity.

5. The future paradigm of DT incorporated robotics

Given all of the emerging trends and potential challenges, it can be stated that the viability of such RDTs can be best utilized if the most emerging practices are unified into collective frameworks. This occurred in the case of industrial robot telemanipulation, where DT-telerobotics, DT-VR, and gesture control were integrated synergistically and created a viable exploration route. Such a framework can also be established for RDT to ensure long-term and successful research goals for future study. In this context, this paper proposes one major hypothesis about the future paradigm of DT-integrated robotics which is fast blockchain-enabled Metaverse as the next generation VTB.

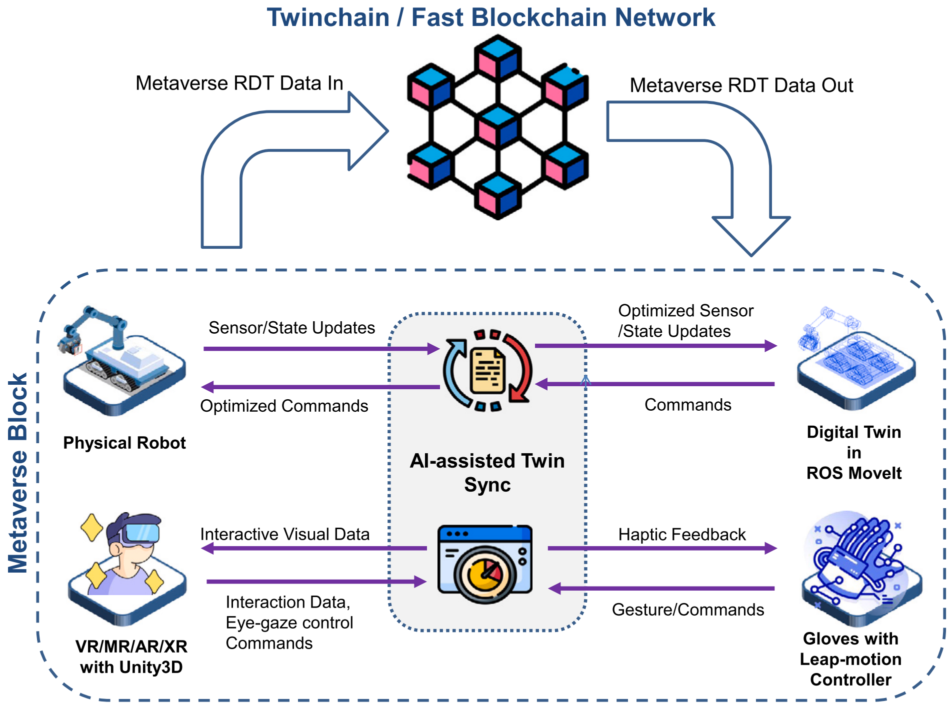


Fig. 12. Proposed Metaverse-RDT architecture.

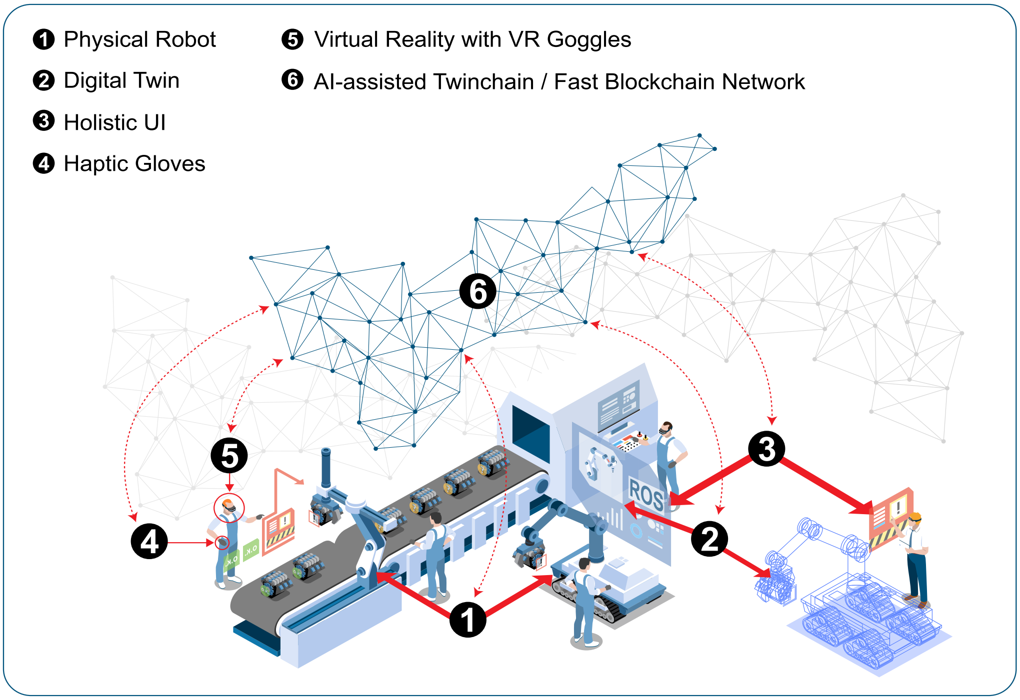


Fig. 13. Metaverse: The next generation VTB application scenario.

5.1. Metaverse: the next generation VTB for DT-robotics

As this paper observed, immersive VR, haptic telerobotics and AI were seemingly the most trending, frequent and versatile approaches in DT incorporated Robotics. Thus a framework that combines all these trends may have great promises for the future challenges. Considering such prospects, this research deemed integration of Blockchain and Metaverse as well as similar technologies a potential future destination for RDTs, especially for next generation VTB developments. Such VTBs may have the ability to integrate most of the viable features of the aforementioned trends and revolutionize design, simulation, analysis and control of robotic applications much like the proposed architecture in Fig. 12. As an application scenario to the architecture readers are requested to refer to Fig. 13 to understand how the architecture works out in a real-world HRI workspace.

Typically due to medium noise, faulty hardware, latency and other issues, there are significant deviation between the DT states and its physical counterpart. Consider a industrial robotic manipulator as marked by (1) in Fig. 13. In many cases, it could be found that the joint angles differ from the DT as marked by (2) to its physical manipulator. Again, in many cases, the physical robot might send false data based on which the DT is updated resulting in huge deviation. Such errors may aggregate to major failures. However, as observed by this study, the benefits of predictive analysis, anomaly detection and fault detection abilities of AI algorithms such as SVM, FFNN and others may be proven to a valuable asset to compensate for such defects and further optimize the system. One may argue that traditional PID and other controllers may also come in handy to fix such issues. However, the interaction data between DT and physical robot may not be the only participants in the future systems. With the wonders of VR/MR/XR/AR-based immersive experience and haptic telerobotics, such technologies are more likely to be implemented in future work-spaces which may have very different types of big data where traditional controllers alone may fail. AI algorithms on the other hand have the ability to be adapt to such changes and find out patterns which are humanly impractical thus providing a better solution.

As depicted in Fig. 12, the DT is proposed to be developed in an environment similar to ROS MoveIt which provides added benefits of in-built trajectory optimizer and collision prevention mechanisms [129]. The bidirectional sensor/state updates between robot and its DT are optimized by the AI block that reduces errors and optimize commands accordingly. Simultaneously, the interaction data of the VR/MR/AR/XR client which can be developed in Unity3D and the gesture control provided by Leap-motion controller all are fed to the AI block where they are synced and merged to reach collective outcomes. Together these elements form the fundamental components of the Metaverse environment that in general, aims to integrate immersive experience in mixed reality via VR goggles [marked by (5) in Fig. 12] and holistic UI [marked by (3) in Fig. 12] to the functionalities of the other elements such as telerobotic control by haptic gloves [marked by (4) in Fig. 12].

Finally, as the networking medium for the entirety of the Metaverse-RDT data a fast blockchain network such as Twinchain marked by (6) in Fig. 12 is proposed which should provide both data immutability, adequate processing speed and decentralization.

However, it should be mentioned the proposed hypothesis is, in general, a prediction by this paper based on the literature review and may require further verification.

6. Conclusion

This paper delved into a systematic and extensive review of available publications to investigate recent trends of DT incorporated robotics. From the findings, it also identified the potential scopes for future research such as mixed reality and immersive VR applications, DT-aided telerobotic applications, AI implementations, robot work-cell simulation, and so on followed by the challenges and their possible solutions. Finally, the research proposed one hypothesis for the future paradigm of DT incorporated robotics where it described the potential of Metaverse and similar technologies and how they combines all the emerging trends of DTIR into one versatile platform with a concept proposed in this paper. It should be mentioned, however, that owing to a lack of publications, numerous important disciplines of robotics have been excluded from this paper, which may be regarded a limitation of this study. In future, the authors intend to supplement the review with another article that will do a more extensive literature review, assuming that the number of publications for the omitted areas becomes adequate. Nevertheless, the review contribution and framework offered in this paper are expected to have a substantial impact on future research on DT integrated robotics.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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