Enabling Robots to become more human and obtain superhuman capabilities for terrestrial and space applications using advanced AI/ML*

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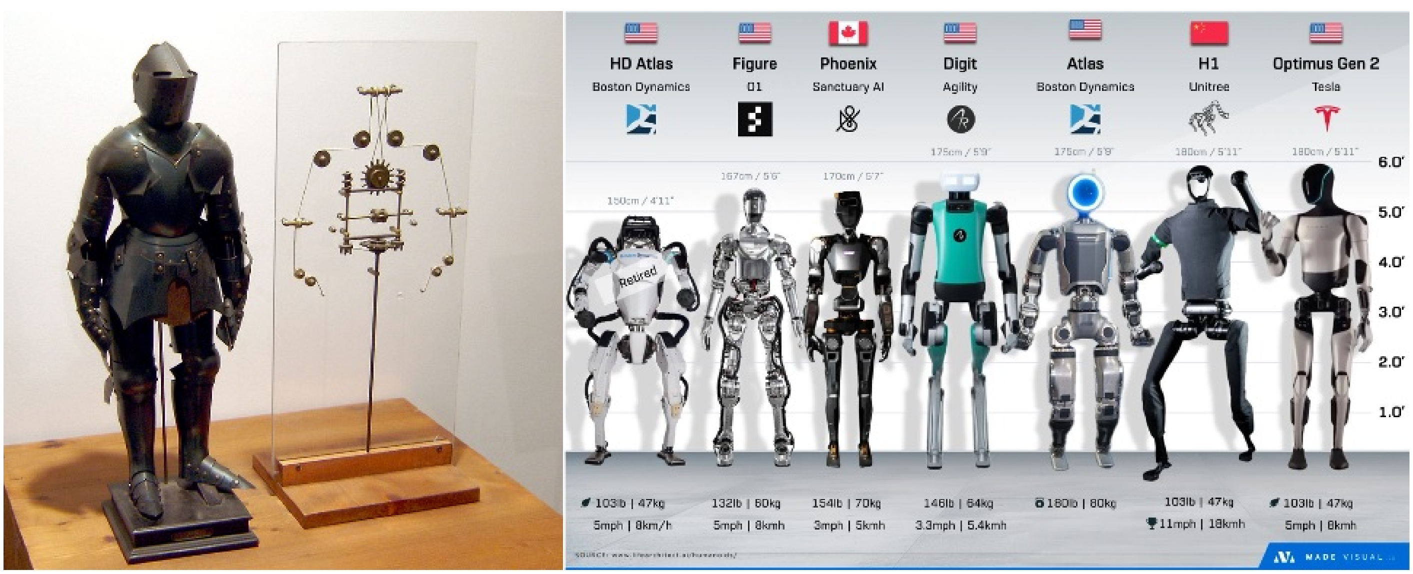
Abstract

Multiple advanced robotic applications exist in the commercial world. For example, in the film industry, Figure 1 shows the robots used in the movie Transformers: Rise of the Beasts, the seventh of the series, filmed in Machu Picchu, Perú, where so called Autobots and Maximals protect an artifact known as the Transwarp Key (Sci-fi: an ancient Cybertronian technology device originally used by the Cybertronians to reach Energon rich planets, by creating a space-time portal) from the villainous Terrorcons. An example of an Autobot is Optimus Prime (vehicle form: big rig truck) shown in Figure 1 in the middle on top of the Maximal called Optimus Primal (animal form: gorilla). An example of Terrorcons, see Figure 1 left, is their leader called Scourge. Going back in history over half a millennium, Leonardo da Vinci designed his knight, a humanoid automaton clad in a suit of knight's armor and operated by pulleys and cables, around 1495, capable of sitting, standing, and independently moving its arms. Figure 2(a) shows it. For a reconstruction of Leonardo's sophisticated, cohesive mechanical design work for functioning automata from his notebooks, see, e.g., [6]. His largest collection of notes are compiled in his Codex Atlanticus. A version in the English language can be found, e.g., in [7]. For a broad reference of the field of humanoid robotics you can consult, e.g., [8, 9]. To successfully design and build humanoid robots, multiple areas of advanced robotics research and technology are necessary to master beyond general robotics including foundations of their kinematics, kineto-statics, and dynamics, advanced simulator environments, biped balance control, cooperative object manipulation with multi-finger hands, model and control of dual-arm and multi-robot systems, human-humanoid interaction (HHI), humanoid intelligence, among several others. In Figure 2(b) the main key humanoid robot representatives in recent years up to 2024 [10] are summarized.

Another area of profound impact of robotics technologies on human society is the area of self-driving cars, also known as autonomous cars (ACs), robotaxis, among others. ACs operate with reduced or no human intervention to perceive the environment, control the vehicle, and in summary, navigate from origin to destination. It has been a while since DARPA organized the Grand Challenge

*This abstract has been granted permission for public release. The author has been leading for decades the conception, design, and development of the most advanced autonomous space robotics programs and missions flown with NASA, ESA, and DLR. Among many others, via personal written interaction with the Office of the German Federal Minister of Research and Technology in 1988, he proposed and launched the First Federal Program for AI/ML Research and Technology Development in Germany [1]. Several consortia were then built and financed. In particular his with DLR and Siemens Corporate R&D in Munich, Germany focused on learning control and advanced applications in robotics also for terrestrial, industrial environments. He is the youngest individual worldwide in history to be awarded the IEEE Fellow Prize ("Nobel" Prize in Engineering) [2] with mention "for leadership in neural and parallel computation, and pioneering contributions to autonomous space robots". He launched and led as Chief Scientist, EiC a scientific journal on AI/ML for 15 yrs. published by Elsevier Science [3]. Most recently, his systems engineering work led to the design of the next gen autonomous Mars helicopters [4] under NASA JPL program management in Pasadena, California.

Figure 1: Transformers filmed in Machu Picchu, Perú [PAR] [5]



(a) (b)

Figure 2: Humanoid Robots (a) Leonardo's Knight (b) Status Quo in 2024 [MAVI] [10]

Figure 3: DARPA Urban Challenge (a) CMU's Boss (b) Stanford's Junior (c) Virginia Tech's Odin (d) Computing system (e) Drive-by-wire system and the interface for manual vehicle operation [12]

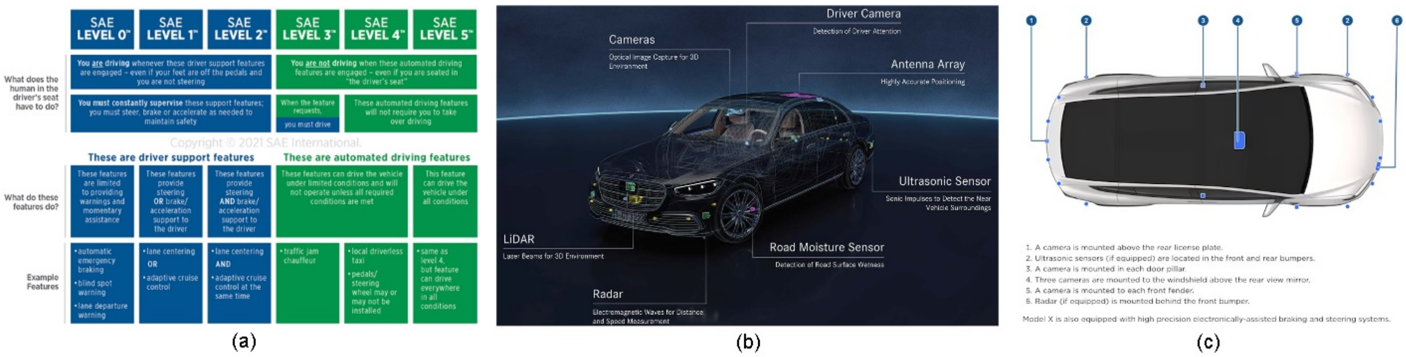


Figure 4: Self Driving Automobiles (a) SAE J3016 Levels of Driving Automation (b) Mercedes S-Class Drive Pilot (c) Tesla Model X Autopilot

races of Autonomous Vehicles (AVs), three of them in the years 2004, 2005, and 2007 [11]. The third and final one was called the DARPA Urban Challenge since it extended the initial challenge to autonomous operation in a mock urban environment. Figure 3(a), (b), (c) show the three competition winners of that third race: CMU's Boss (1st place), Stanford's Junior (2nd place), and Virginia Tech's Odin (3rd place), respectively [12]. MIT's Talos finished fourth (no prize). Figure 3(d) shows the computing system, and Figure 3(e) shows the drive-by-wire system and the interface for manual vehicle operation inside the Diesel Volkswagen Touareg R5 of Stanford's Stanley, winner of the 2005 Grand Challenge race. Complementary, additional robotic technologies are used for increasingly autonomous flying vehicles including unmanned aerial vehicles (UAVs), operating not only on planet Earth, but also in other celestial bodies as per my recent systems engineering design and verification work on the next gen Mars helicopters at NASA JPL outlined later in this paper. For example, on Earth, guidance for global navigation can be added using GPS/INS like in my design and development work hands-on leading and executing a DoD classified avionics program with subcontractors including Lockheed Martin and SAIC, which also incorporated mission-critical, real-time AI/ML chips, see [12]. SEA International, formerly the Society of Automotive Engineers, a global professional association and standards organization, has defined six levels of driving automation as shown in Figure 4(a). At level 0 the human driver does all the driving, at level 5 the vehicle computing brain does all the driving. Level 0, 1, 2, and 2.5 (in addition to the six) are sometimes called minimal, basic, additional, and advanced assistance, respectively, and level 3, 4, and 5 conditional, advanced, and full automated driving, respectively. Figure 4(b) and (c) show two examples of commercial AC products and sensorics used in them: the Mercedes S-Class Drive Pilot and the Tesla Model X Autopilot, respectively. These examples show clearly which sensors leading AC manufacturers use for perception of the environment to be able to navigate safely: cameras, LIDAR, radar, ultrasonic, among others.

The computing power and algorithmic requirements to process such data have been challenging from the very beginning. That is why I had to design and build completely new – the world had never seen before – scalable, mission-critical, real-time supercomputers and conceive new algorithmic approaches to precisely target all those requirements. Figure 5 show some key aspects of those developments, in particular one of those supercomputers used in a NASA-ESA-DLR Spaceshuttle/Spacelab mission – shown is a highly preliminary, intermediate prototype – which was way ahead of its time, several decades, beat the most powerful supercomputer at that time easily, the Cray, since it was 100-, 1,000-, ... times faster, because I designed it as an scalable parallel distributed computer architecture. Each of the parallel processors in my supercomputer was at around that time more powerful than the best Cray processor and the Crays were at that time single processor machines. On top, I designed computing nodes with at least an order of magnitude even more powerful than the parallel processor nodes via accelerating hardware and specialized algorithmic libraries. Germany had at that time a national laboratory in charge of supercomputing, i.e., to compete worldwide and build those machines like Cray, with hundreds if not thousands of scientists and engineers working on it, but they never quite made it, i.e., they could not beat the Cray. And those general supercomputers like the Cray and others are in principle only simulation engines, not for real-time operation of real tasks. My supercomputers could do all of that 100%, what the Crays could do, only they could do it much, much faster, and on top, they could do hundreds of other things since designed for mission-critical, real-time tasks with interfaces to almost any sensor available, and to other computing systems linked to space telecom or computer graphics rendering for virtual reality, to implement the architecture we designed, built, and operate, the DLR telerobotics ground station, which allowed us to monitor fully autonomous robotic operation in space from Earth as well, because that is the way we conceived it, to be able to predictively control the future i.e., what we see on Earth is what will happen in the future in space, in this case in a workcell of the Spacelab aboard a Spaceshuttle.

There are so many aspects that until today the world has not been able to reproduce. It was a requirements-driven design, it was never my intention to beat the U.S.A. so badly, key results of that fantastic success were presented in the U.S.A, but obviously in Europe too at ESA/ESTEC in Noordwijk, The Netherlands, among others, literally a few hours after that NASA-ESA-DLR Spaceshuttle/Spacelab mission had been completed, as NASA flew me to Pasadena, CA to an invited special presentation at the Jet Propulsion Laboratory (JPL) [13]. My experience designing special-purpose processors at Siemens AG was without a doubt very beneficial where some computer architectures we designed included ASICs and even the ASICs were being designed with a powerful AI-for-VSLI tool I conceived, designed, and coded at the Karlsruhe Institute of Technology (KIT) before joining Siemens AG. The Artificial Intelligence (AI) algorithms I introduced for those developments were even provable in the mathematical sense, something AI/ML typically never dreamed to have. Btw., one ”half” of the commercial version of that supercomputer was immediately acquired by Mercedes-Benz Corporate R&D in Untertürkheim by Stuttgart, Germany precisely to initiate their AC developments early enough to become currently one of the leading manufacturers of self-driving cars. In August this year 2024, Mercedes-Benz became the first international car maker to obtain approval for Level 4 automated driving testing for designated urban roads and highways in Beijing, China [14]. For advances in multiple disciplines of autonomous robotics, for example in computer vision, perception, artificial intelligence, and deep learning you can consult, e.g., [15, 16, 17], in control, traction, propulsion, and navigation [18, 19], in connected heavy vehicles, materials, manufacturing, business, and law [20, 21, 22].

Now let us turn our attention for a moment to the current need, developments, and accomplishments of space robotics, in particular, In-space Servicing, Assembly, and Manufacturing (ISAM) capabilities. Spaceflight missions are becoming increasingly more ambitious to support exploration and hopefully soon colonization, national security, and commercial space goals. Science and human exploration/colonization missions need payloads larger than any foreseeable launch vehicle fairing. National security missions require persistent, mobile and resilient assets. Commercial space missions require cost-effective ways to update to the latest technology on orbit [23]. Compared to the traditional approach of launching a payload without the intent to ever upgrading it, ISAM can significantly expand its performance, availability, and lifetime creating a better foundation for sustainable, reusable space servicing, exploration and colonization. For a review of spaceflight robotic systems to grapple spacecraft, e.g., free-flying client satellites, you can consult, e.g., [24]. The DARPA’s Robotic Servicing of Geosynchronous Satellites (RSGS) program is a public-private partner-

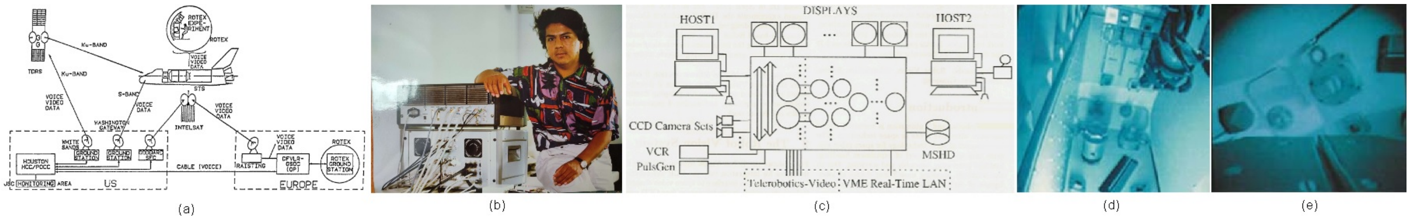
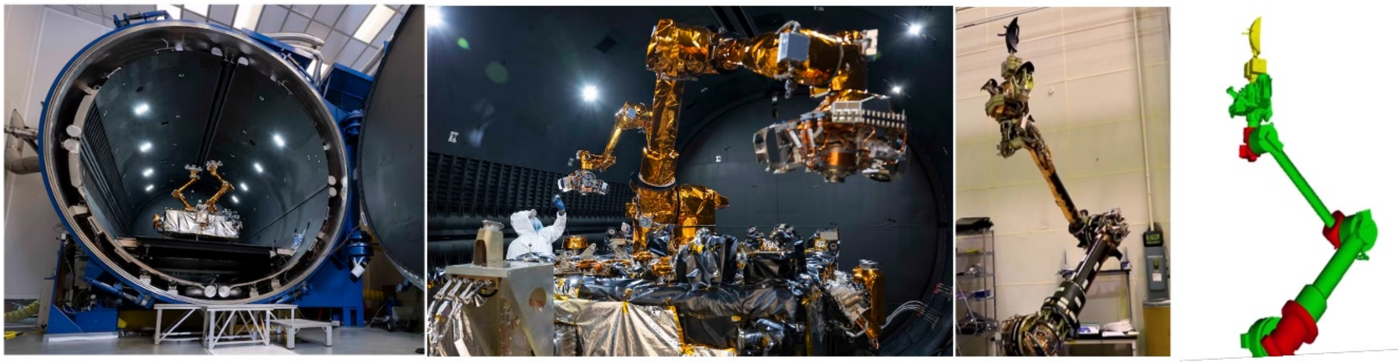


Figure 5: Space autonomous robotics technologies basis for current and future terrestrial autonomous cars and UAVs (a) Interfaces for NASA-ESA-DLR Spaceshuttle/Spacelab flight – Space robotics technology demonstration: ROTEX flown on DLR D2 mission (b) Intermediate prototype of mission-critical real-time AI/ML supercomputer (c) Top Level schematic diagram of mission-critical real-time AI/ML supercomputer (d) Spacelab ROTEX workcell stereo camera image (one of two shown) (e) Spacelab ROTEX robotic hand tiniest stereo camera image (one of two shown)

Figure 6: Satellite Servicing [NGC] [25] (a) Extending the life of a satellite (b) Mission Extension Vehicle (MEV) (c) Mission Robotic Vehicle (MRV) (d) Mission Extension Pod (POD)

ship between DARPA and Northrop Grumman's SpaceLogistics subsidiary, see Figure 6, after Space Systems Loral (SSL) ceased to be the commercial partner due to financial issues in 2019, with the Naval Research Laboratory (NRL) developing the robotic servicing payload. Figure 6(a) shows how the life of a geosynchronous satellite can be extended whereas Figure 6(b), (c), and (d) show the Mission Extension Vehicle (MEV), the Mission Robotic Vehicle (MRV), and the Mission Extension Pod (MEP), respectively [25]. The platform for the RSGS payload is the MRV. This program is developing a commercially owned and operated Robotic Servicing Vehicle (RSV) made of a privately developed spacecraft (commercial partner) and dexterous robotic arms and supporting technology (DARPA) to enable dozens of high-resolution inspection, anomaly correction, cooperative relocation, and upgrade installation missions over several years. The RSV is to perform safe, reliable, useful and efficient operations, with the flexibility to adapt to a variety of on-orbit missions and conditions.

The MEV uses a suite of integrated proximity sensors and a simple mechanical docking system to reliably and safely rendezvous and dock with a client satellite running low on fuel, taking over its attitude and orbit maintenance. It is compatible with nearly 80% of all GEO satellites on orbit today. It carries fuel for a planned 15+ year service life. When a customer no longer requires life-extension service, the MEV undocks and proceeds to its next client. The MRV leverages the heritage Rendezvous Proximity Operations and Docking (RPOD) system of the MEV, its predecessor, incorporating a robotic module in place of the MEV's docking system. Its sophisticated robotics expands the benefits of the MEV offering detailed robotic inspection, augmentation, relocation, repair, active debris removal, refueling, and docking with non-standard client spacecraft interfaces. Its main function is to install the MEPs or other augmentation payloads on current operational satellites. The MEP is a small, customer-owned, customer-controlled propulsion augmentation device installed by the MRV on a client on-orbit and low on fuel running satellite. It provides 6 years of life extension for a typical 2,000 kg satellite in GEO. It uses electric propulsion to provide orbit control and momentum unloading for a client satellite. The customer can control it using a self-contained C- or Ku-band telemetry and command system. Under DARPA funding, the U.S. Naval Research Laboratory (NRL) Naval Center for Space Technology (NCST) completed the development of the RSGS



(a) (b) (c)

Figure 7: DARPA's Robotic Servicing of Geosynchronous Satellites (RSGS) Integrated Robotic Payload (IRP) (a) In the cryogenic thermal vaccum chamber (b) Final testing at the NRL's Naval Center for Space Technology (NCST) (c) Integrated Robotics Workstation, Operator View

(a) (b) (c)

Figure 8: NASA Satellite Servicing Ambitions [27] (a) Technologies (b) Missions (c) Architectures

Integrated Robotic Payload (IRP), see Figure 7, a spaceflight qualified robotics suite capable of servicing satellites in orbit [26]. NASA's vision, as reference for the OSAM-1 mission and others, shows in Figure 8(a) technologies supporting emerging space industries including satellite servicing and assembly. These include close inspection, free-flyer capture and relocation, delivery and aggregation, maintenance and repair, refueling and fluid transfer, installation and upgrade, as well as manufacturing and assembly. Figure 8(b) shows three related missions: two NASA's missions (OSAM-1 and OSAM-2) and one DARPA's mission (RSGS/MRV). Figure 8(c) shows Rendezvous, Proximity Operations, and Capture (RPOC)- and ISAM-enabled or enhanced architectures/platforms for civil space, commercial and national security applications.

DARPA and NASA have entered into an interagency collaboration [28], through which NASA lends subject matter expertise to DARPA's RSGS program focusing on supporting the final phases of technology development, integration, testing, and the eventual demonstration to show that the RSGS spacecraft enhances capabilities for in-orbit satellite inspection, repairs, and upgrades as part of the nation's in-space servicing, assembly, and manufacturing (ISAM) capabilities to benefit commercial, civil, and national objectives. Previous- and unfortunately, both NASA's related programs, OSAM-1 and OSAM-2, were cancelled. Due to continued technical, cost, and schedule challenges as well as uncertain ROI of flying OSAM-1 technology, NASA cancelled the On-orbit Servicing, Assembly, and Manufacturing 1 (OSAM-1) mission [29] after rejecting a proposal to revise the mission to meet a 2026 launch date. OSAM-1, see Figure 9(a) and (b), seeked to rendezvous with, refuel, and relocate Landsat 7 [30], a U.S. government-owned satellite and built by Lockheed Martin Space Systems, see Figure 9(c), (d), and (e), to demonstrate the feasibility of on-orbit refueling, satellite relocation, and life extension as well as the assembly of a communications antenna using a robotic arm. The NASA's On-orbit Servicing, Assembly, and Manufacturing 2 (OSAM-2) mission formed a private-public partnership, see Figure 10(a), with the main goal of launching a small spacecraft to

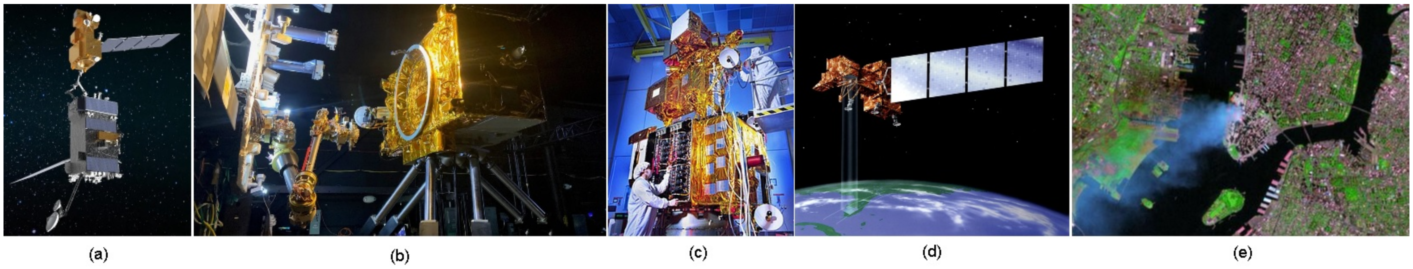


Figure 9: NASA's On-orbit Servicing, Assembly, and Manufacturing 1 (OSAM-1) (a) Grappling Landsat 7 (b) Grapple test of the spacecraft's robotic servicing arm (c) Landsat 7 satellite (d) Landsat 7 in orbit (e) Landsat 7 imagery – Twin towers still smoking one day after the 9/11 attack [NASA, USGS]

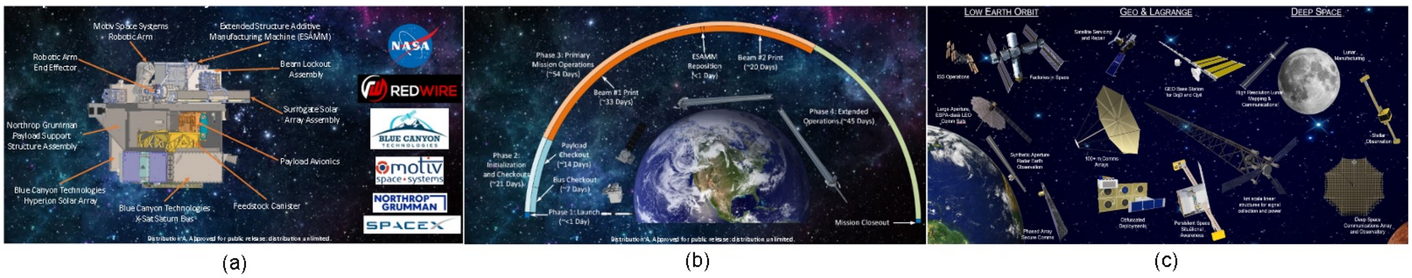


Figure 10: NASA's On-orbit Servicing, Assembly, and Manufacturing 2 (OSAM-2) (a) Spacecraft, Subsystems, Industrial Partners (b) Concept of Operations Timeline (c) Infusion Potential [NASA, Redwire]

manufacture and assemble spacecraft components in Low Earth Orbit (LEO). Robotic technologies were being developed by the consortium partners to autonomously manufacture and assemble hardware, components, and tools in space, before NASA cancelled it without flight demonstration [31]. In particular, additive manufacturing (AM), i.e., 3D printing was to build and assemble complex components in space, deliver on-demand hardware, and allow for structures larger than current rockets can deliver and deploy to orbit. OSAM-2 had defined ambitious goals as shown in Figure 10(b) and (c). For its navigation, communication, and intelligence satellite system programs and missions, the U.S. military still remains uncertain about adopting other in-space servicing, assembly and manufacturing (ISAM) services beyond basic satellite refueling [32]. Budget constraints and technical uncertainties are the main impediments against services like component replacement or payload repairs. The U.S. military's top priorities remain its protect and defend architecture and the modernization of legacy systems. On the technical side, any commercial partner attempting close-range operations needs to earn that trust, which is a significant hurdle. On the budgetary side, only a budget allocation change will improve the situation, also once the technology is readily available at the level of maturity required to become operational.

There have also been completely successful space robotics missions related to satellite servicing in history. For example, the DARPA's Orbital Express program focused on robotic on-orbit refueling and reconfiguring [33, p. 15]. The Orbital Express advanced technology demonstration designed, developed, and tested on orbit a prototype servicing satellite (ASTRO) and a surrogate next-generation serviceable satellite (NextSat). Servicing non-supporting satellites or space debris is obviously much more complex and highly needed. We devote some effort to elaborate on upcoming space robotics technologies for that more complex purpose based on previous own successful flown space missions directly supporting that goal. The NASA Spaceshuttle Mission STS-55 flight [34] DLR Robotics Technology Experiment ROTEX [35, 36, 37], aboard ESA's Spacelab [39] is summarized in Figure 11. It was originally conceived as a space telerobotics demonstration incorporating innovative, advanced predictive control concepts [35]. With my inclusion as head of the research and technology developments for the toughest add-on experiment, fully autonomously catching a free-flying floating under microgravity using machine intelligence [36, 37], the ROTEX mission goals could not have been more ambitious, cf. Figure 11 left. I was honored to take on the associated tasks and delivered

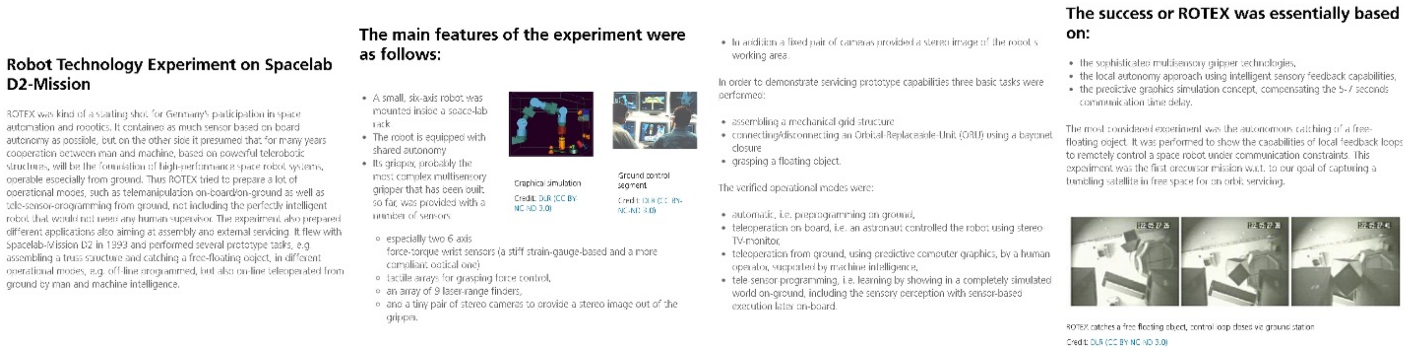


Figure 11: NASA-ESA Spaceshuttle-Spacelab Mission Robotics Technology Experiment (ROTEX) [DLR] [37, 38]

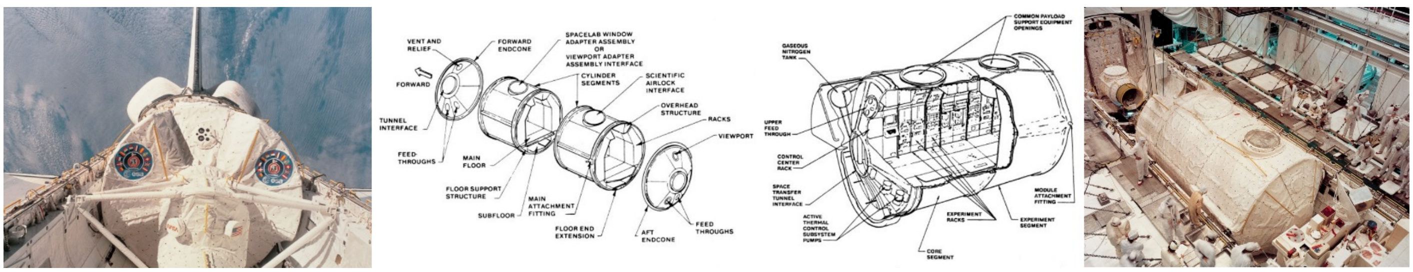


Figure 12: ESA Spacelab aboard NASA Spaceshuttle Columbia hosting DLR ROTEX [NASA, ESA] [39]

starting absolutely from scratch, i.e., before me there was no hardware, no software, no algorithms, no interfaces. In particular, we "cannibalized" the RGB graphics interface of the NASA's Spaceshuttle only used to send regular images to Earth to send switchable stereo images, from two stereo camera systems, one of the workcell and one of the space robotic hand. The main features of this space robotics demonstration that flew as an integral part of the so called German D-2 mission are summarized in Figure 11 center. The extraordinary success of this space robotics demonstration was provided by the results obtained as shown in Figure 11 right. Figure 12 shows to the left the cargo bay of NASA's Spaceshuttle where ESA's Spacelab, a reusable space laboratory manufactured by MBB/ERNO fits into. Right of it are schematics of the Spacelab internals and at the far right a photo of the Spacelab is shown, in one of whose racks, the ROTEX space manipulator was hosted and performed the space robotics technology demonstration. From the excerpt of the NASA mission report included in Figure 13 far right: "The arm used teleprogramming and artificial intelligence to evaluate the designs, verification and operation of advanced autonomous systems for future application. The complete automation system of the ROTEX experiment performed extremely well. Several modes were successfully demonstrated including telescience operations from the ground and by the crew. The arm performed extremely well in capturing a free-floating object". The modes of operation included notably fully autonomous without any human intervention, teleoperation from Earth using the telerobotics workstation at the German Space Operations Center (GSOC), Manned Spaceflight Control Center (MSCC), see Figures 11 and 13, and shared, symbiotic control between artificial and human brains (teleoperators and astronauts). Figure 13 shows in addition photos and details of the ROTEX space robotic manipulator, of the ESA's Spacelab ROTEX rack in the simulation as graphics rendering, as emulation/mock up in the lab, control by the teleoperator on Earth/lab and by an astronaut in space aboard the Spaceshuttle/Spacelab during the D2 mission of the STS-55 flight, image sequence from one of two space robotic hand stereo cameras while catching the floating object under microgravity in space during the space robotics technology demonstration, and a NASA digital recording of one of my presentations about the space robotics technologies developed, all of which are used today, in particular for satellite servicing as described in the sequel.

In Figure 14(a) one can clearly appreciate the high resolution of the rendering of the workcell during the ROTEX space technology demonstration so that the teleoperator can comfortably work

Figure 13: NASA-ESA-DLR Mission – Robotics Technology Experiment (ROTEX) [DLR] [34]

controlling the space robotic manipulator by only looking at the display showing in the rendering what will happen in the future in space, in the Spaceshuttle/Spacelab workcell, thus controlling the future. The only other key aspect not shown there is the overlay of the computer vision (CV) processing results on top of the computer graphics while catching the floating object under microgravity. That degree of virtual reality (VR) rendering resolution, now even with augmented reality has been preserved in the UIs across all satellite servicing subsystem displays as can be seen on the left display in Figure 14(b) which shows synchronously in the computer simulation and on one of the two displays what is happening in reality: a servicing satellite with a servicing robotic manipulator on top (color orange) coming from the left mating a target client satellite coming fom the right. The movement of both satellite mock ups in the simulation facility is provided by two robotic systems. Figure 14(c) shows the robotic manipulator on top of the servicing satellite proceeding to capture the target client satellite in a fully autonomous fashion processing via real-time computer vision (CV) and machine intelligence the stereo camera images and data from other sensors like LIDAR. As comparison, the ROTEX space robotic hand had multiple sensors built-in including also a stereo camera pair and laser range finders for the pose (position and orientation) determination of the free-floating object to catch. The sizes involved with both manipulators: ROTEX and the satellite servicing robotic manipulator directly suggest that capturing a non-cooperative target client satellite require similar accuracy determining where and how to control the robotic hand, i.e., its fingers, to move to. The stereo camera systems of both manipulators are pointed to by green arrows. Figure 14(d) shows another area in which the original results of my world leading R&D work led to, planetary terrain mapping. On the top left, depth maps results are shown of three-dimensional visible surface reconstruction algortihms when applied to stereo camera images [40]. On the right and bottom left, the High Resolution Stereo Camera (HRSC) developed also at DLR is shown and some mapping results, respectively, as this highly specialized space stereo camera was used to map the entire surface of the Red Planet when flown with the ESA's Mars Express mission [41].

The German Aerospace Center (Das Deutsche Zentrum für Luft- und Raumfahrt DLR, in German) currently offers in its largest location in Oberpfaffenhofen by Munich, Germany two facilities for the purpose of satellite servicing simulation: the On-Orbit Servicing SIMulator (OOS-SIM) at the Institute of Robotics and Mechatronics where I myself was based for a decade and the European Proximity Operations Simulator (EPOS) at the German Space Operations Center (GSOC) where I with my team helped build the MSCC (Manned Spaceflight Control Center) and used it as payload operators of space robotics missions, e.g., during the NASA STS-55 flight of the Spaceshuttle Columbia. How the operations of on-orbit servicing missions are performed, can be consulted in, e.g., [42]. The DLR OOS-SIM and EPOS facilities are shown in Figure 15. Two robotic systems with similar requirements like OOS-SIM and EPOS I myself had to design and develop to simulate the catching of the free-flying object under microgravity on Earth in one of our labs at the Institute of Robotics and Mechatronics, one robotic system simulating the ROTEX space robotic manipulator with the ROTEX multisensory gripper/robotic hand attached, see Figure 14(c), and a second robotic system simulating the trajectory of the free-flying object while all multisensory and control data was also passing through a simulation of the delays with jitter expected during the actual space mission. The controllers of both robotic systems were very powerful since they too were based on scalable parallel computing hardware, I designed them that way. The parallel software I designed, coded,

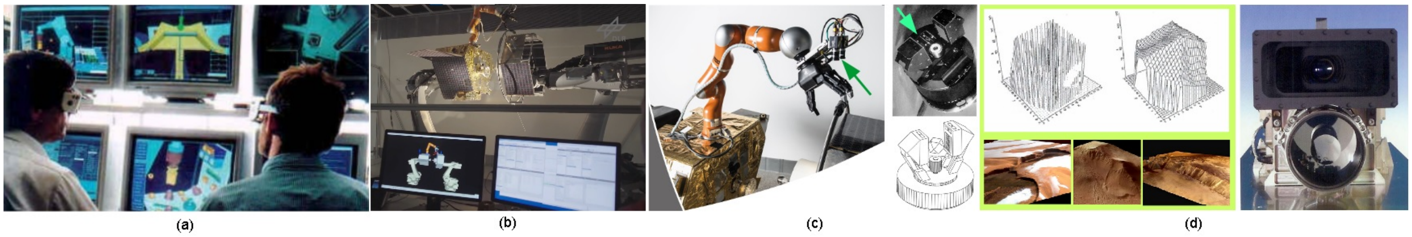


Figure 14: Space Robotics Technologies (a) Virtual Reality (VR) (b) Satellite Servicing (c) Computer Vision (CV) (d) Planetary Terrain Mapping [37, 43, 44, 45]

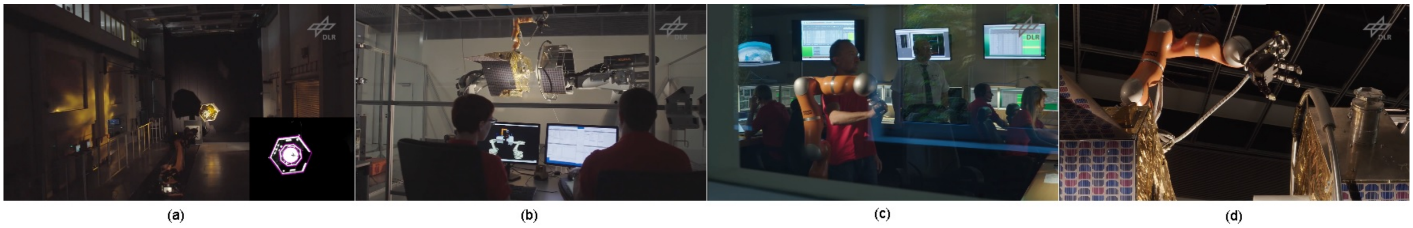
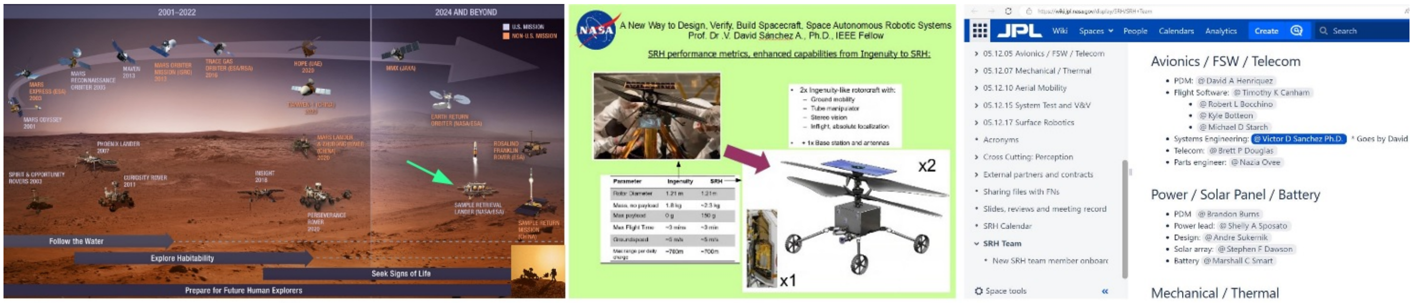


Figure 15: DLR OOS-SIM [46] and EPOS [47] (a) Rendezvous in the European Proximity Operations Simulator (EPOS 2.0) (b) On-Orbit Servicing SIMulator (OOS-SIM) (c) Telepresence (d) Target satellite capture

and integrated straightforwardlly. We as a team were then best prepared for the actual space mission aboard the Spaceshuttle/Spacelab. That is in essence what OOS-SIM and EPOS do with some further sophistication in terms of the newer equipment used: larger rooms, larger robots, among others. The main overall improvement is in being reusable for different satellite servicing missions. Figure 15(a) and (b) show the DLR EPOS and OOS-SIM facilities at the DLR Oberpfaffenhofen center, respectively. Figure 15(c) and (d) show the operation via telepresence from the ground control center and fully autonomous, CV-guided operation – if no human intervention was chosen –, respectively. If human intervention is requested, e.g., via telepresence, Figure 15(d) which only shows one frame would still look the same, but the entire final trajectory of the robotic manipulator to capture the target client satellite would be different guided by the human brain and arm of the operator on the ground, see Figure 15(c).

Space autonomous robotics technologies are also used at the forefront of space exploration, e.g., during my and related work on the design and development of next gen Mars helicopters in the context of the NASA's Mars Exploration Program (MEP) [4, 48], see Figure 16. Figure 17(a) shows three different solar-powered Mars helicopter models. Figure 17(b) shows the Ingenuity Mars Helicopter [50], which was delivered to Mars on February 18, 2021, attached to the underside of the Perseverance Mars rover [51]. It performed its first and last flights on April 19, 2021 and January 18, 2024, respectively, accumulating a total of 72 flights autonomously to execute flight plans designed and sent to it by the Jet Propulsion Laboratory (JPL). During a rough landing on the 72nd flight, a rotor blade broke off permanently grounding Ingenuity. It also shows commercial off-the-shelf (COTS) subsystems integrated into the Ingenuity design below. Figure 17(c) shows one of two Sample Recovery Helicopters (SRHs) [52] that serve as backups to the Perseverance Mars rover to transport sample tubes to the Sample Retrieval Lander (SRL) [53] during the planned NASA-ESA Mars Sample Return (MSR) Campaign [54, 55] and a sample tube below. Figure 17(d) shows the six-rotor Mars Science Helicopter (MSH) concept [56] for future Mars missions to serve as an aerial scout and carry larger payloads including science instruments to study terrain that Mars rovers cannot reach. Figure 17(e) shows the nuclear-powered Dragonfly helicopter [57] to fly in the skies of Saturn's largest moon, Titan.

The goal of the three-mission NASA-ESA Mars Sample Return (MSR) Campaign is to bring first Mars material samples, scientifically curated and collected by NASA's Mars Perseverance rover, safely back to Earth for detailed study, among others to determine whether ancient life ever arose on Mars. An outline of the three missions follows. The sample collection mission, Mars 2020, landed the



(a) (b) (c)

Figure 16: Mars Sample Return (MSR) Campaign – Sample Recovery Helicopters (SRHs) (a) MSR in NASA's Exploring Mars Together Vision (b) From Ingenuity to SRHs for NASA-ESA MSR (c) SRHs Systems Engineering Task at JPL [48, 49]

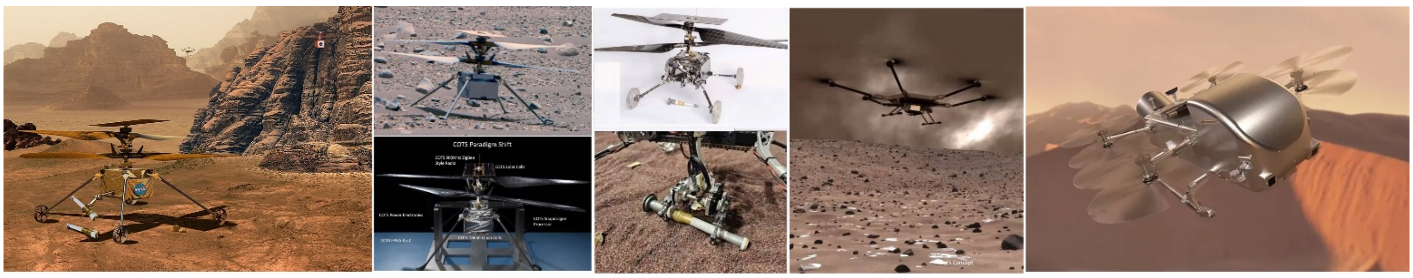

(a) (b) (c) (d) (e)

Figure 17: NASA's Mars and Saturn Titan Helicopters (a) Three solar-powered Mars helicopter models (b) Ingenuity Mars Helicopter (c) Sample Recovery Helicopter (SRH) (d) Mars Science Helicopter (MSH) (e) Dragonfly helicopter for Saturn's Titan moon [NASA, JPL, APL]

Mars rover Perseverance and the Mars helicopter Ingenuity on the Red Planet. The sample retrieval mission is to transport the Sample Retrieval Lander (SRL), the Mars Ascent Vehicle (MAV) [58], the Sample Transfer Arm (STA) [59], and two Sample Recovery Helicopters (SRHs) to the Red Planet. And finally, the return mission which is to launch the Earth Return Orbiter (ERO) [60], the first interplanetary spacecraft in a full round trip Earth to Mars and back to Earth to capture an object in orbit around another planet, in this case the Orbiting Sample (OS) container [61].

The Mars Ascent Vehicle (MAV) is a two-stage, solid-fueled rocket – the two solid rocket motors are called SRM1 and SRM2 –, to be catapulted off the SRL first upward before igniting its motors to reach low Mars orbit (LMO). The SRL mission with the MAV aboard needs to deliver a larger payload than previous Mars landers. Due to the challenging conditions of Entry, Descent, and Landing (EDL) on Mars, it will require innovative approaches to manage the high mass during entry including larger parachutes, longer powered descent phases, and potentially innovative aerodynamic decelerators. The SRM1 propells the MAV away from the Martian surface, while SRM2 spins MAV's second stage to place the OS container in the adequate Mars orbit, allowing the ERO to find it. The Sample Transfer Arm (STA) is a 7-dof robotic arm with a gripper, multiple sensors including stereo cameras to capture and handle the sample tubes at different angles, to insert them into the Orbiting Sample (OS) container and then close its lid before lifting-off from Mars aboard the MAV. The Earth Return Orbiter (ERO) is to return the Mars sample tubes to Earth after the MAV has delivered the OS to Mars orbit and executing the autonomous rendezvous of the OS in Mars orbit. The Capture and Containment and Return System (CCRS) [62] is the payload on the Earth Return Orbiter (ERO) that will contain the sealed Mars samples. Robotic operations within the CCRS allow the OS to be assembled into the Earth Entry System (EES) spacecraft. When flying past Earth, the ERO will release the Earth Entry System (EES). The Earth Entry Vehicle (EEV) [63] will land on Earth without a parachute and utilize a 3-D woven Mid-Density Carbon Phenolic (3DMCP) Thermal Protection System (TPS) [64]. Figure 18 and Figure 19 show key features of the MSR campaign.

Since very early in the game, my world leading research and technology development work has

(a) (b) (c) (d) (e)

Figure 18: The Mars 2020 Perseverance Rover and the Sample Retrieval Lander (SRL) (a) Rover collecting and storing samples in specially designed sample tubes (b) Mast head of rover watching the SRL landing on the Martian surface (c) Orbiting Sample (OS) container with sample tubes inserted by the Sample Transfer Arm (STA) (d) Perseverance rover and SRL after all sample tubes have been inserted into the OS (e) Mars Ascent Vehicle (MAV) atop the SRL preparing to be launched to bring OS container to Low Mars Orbit (LMO)

(a) (b) (c) (d) (e)

Figure 19: The Mars Sample Return (MSR) campaign and the Earth Return Orbiter (ERO) (a) Mars Ascent Vehicle (MAV) catapulted off the Sample Retrieval Lander (SRL) first upward, launched to Low Mars Orbit (LMO) (b) Stage separation, second stage initiating a spin up via its side mounted RCS thrusters (c) ERO starting an autonomous rendezvous of the Orbiting Sample (OS) container in LMO (d) ERO after capturing OS using cameras and LiDARs to track it and OS safely transferred within the Earth Entry System (EES) (e) The Earth-return spacecraft releasing the Earth Entry Vehicle (EEV) on its way back to planet Earth

been focused on computer vision (CV), artificial intelligence (AI), machine learning (ML) and robotics. Particular interest has been centered in learning control [65] to augment automation [66] and autonomy of space [67] and terrestrial [68] robots and also for the manufacturing and automation [69] as well as the space defense [70] industry. Several AI/ML topics, from the initial learning methods including reinforcement [71] to more recent ones, have significantly influenced advances in modern robotics, e.g., as described in [72], in deep reinforcement learning [73], in robot perception and cognition [17], in cognitice robotics [74], in intelligent control design [75], in adaptive and reactive control [76], in AI for future gen robots [16], among mutiple others. My personal written interaction with the Office of the German Federal Minister of Research and Technology ("Bundesminister für Forschung und Technologie") had already in 1988 launched the First Federal Program for AI/ML Research and Technology Development in Germany [1] and later to the establishment of new university departments of AI/ML all over Germany [77]. I launched and led as Chief Scientist, EiC a scientific journal on AI/ML for 15 yrs. published by Elsevier Science [3]. Designing and developing machines that operate independently and make decisions without human intervention is reshaping our lives, still slowly, and has produced among others drones delivering packages, robots cleaning in the households, and autonomous vehicles navigating city streets. A market volume for this type of autonomous world is being unlocked, a $10 trillion opportunity by 2035 [78]. Generalizable robots are very adaptable and versatile, because they can learn skills that apply to situations beyond their initial training data. According to some investment management firms specializing in disruptive innovation, the convergence of AI and hardware enables generalizable robotics, the productivity continues being improved by AI, and a market opportunity for generalizable robotics of more than $24 trillion in revenue anually is being created [79, p.114]. On the other hand, robotaxi platforms can redefine personal mobility and generate $28 trillion in enterprise value during the next 5 to 10 years [79, p.123]. The robotics field is becoming a highly attractive investment field with a volume of $12.9 billion of investment into robotic companies alone in 2023 [80]. Advances in robotic technologies for vertical space and terrestrial applications are analyzed and several new or unknown ones are conceived, described that constitute the basis for enabling robots to become more human and continue obtaining superhuman capabilities under our control [81] for terrestrial [82] and space [83] applications using advanced AI/ML [84] and allowing for the exponential growth and market value of associated programs and companies including the incorporation of huge operational capability and adaptability for the automated, robotic manufacturing factories of the future [85].

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