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4 Robotic Revolutions - Proposing a holistic phase model describing future disruptions in the evolution of robotics and automation and the rise of a new Generation 'R' of Robotic Natives

Dominik B. O. Boesl, Bernd Liepert*

Abstract— **This paper describes the holistic phase model of the '4 Robotic Revolutions' - disruptive waves of evolution in robotics and automation - and their impact on society, economy and other areas of human life over the next 50 years. Furthermore, an explanation is provided, why a new Generation 'R' of Robotic Natives will grow up in daily contact with automation technology perceiving technology as valuable enrichments for their lives.**

The paper closes with an outlook into reasons why humankind has to ignite a holistic discourse about the responsible application of these disruptive technologies in order to shape a sustainable future enhanced (and not threatened) by robotics and automation. In consequence, the need for self-regulation in the sense of Technology and Robotic Governance will arise.

Keywords— Future of Robotics; 4 Robotic Revolutions; Generation R; Robotic Natives; Future of Automation; Technology Evolution; Robotic Evolution; Future of Technology; Technology Adoption; Innovation Management; Robotic Governance; Technology Governance; Roboethics; Technology Ethics; ESL.

I. INTRODUCTION

Robotics will change the world! It will unleash the same if not an even more disruptive and transformational power within the next 50 years as mainstream IT-technology and the Internet have in the last half of a century. Nurtured by technological breakthroughs in industrial automation, robotics will permeate other domains. Hence, a new generation of Robotic Natives will grow up in a society that is enriched and enhanced by robotics in every imaginable way. Robotics will be tailored into many everyday objects, thus becoming an integral part of all kinds of appliances.

The direct interaction with any form of robotic and automated system will not intimidate this Generation 'R' [1]. It will perceive self-driving cars, autonomous service robots, automatization in logistics and robotics in retail as just as normal as the internet, smartphones and tablets are for us today. This change will not be limited to the steadily growing field of industrial robotics. Due to a number of technological enablers, e.g. the broad availability of low cost but high performance sensor technologies, robotics will be unchained and liberated from its cells. It will conquer completely new domains until it pervades all areas of life, permeating all parts of the human experience realm [2].

We provide a feasible and holistic model describing four disruptive evolutionary phases of robotic and automation development: the '4 Robotic Revolutions'.

II. ANALYSIS OF MEGATRENDS AS DRIVING FORCES

Predicting the future is impossible. In innovation management, the analysis of the so-called 'Megatrends' [3] provides one commonly accepted method for estimating driving forces that will have impact on the whole planet earth and humanity over the next 15 to 25 years. Extrapolating these trends, it is possible to make predictions for future needs, developments of future markets and overall requirements for technological innovation. Mobility, globalization, global warming, overageing society, urbanization, digital life / connectivity, individualization and orientation towards a healthy lifestyle are an often cited subset of megatrends that will heavily influence the evolution of (industrial) robotics and automation.

New markets will emerge driven by the augmented demand resulting from exuberant worldwide population growth. The United Nations expect the global population will exceed 8 billion people by 2025 and 10 billion around 2060 [4][5]. Different needs will arise from this demographic change: First, an overall rising demand for production capabilities will become immanent, partly driven by the new economic power of some markets (mainly in Asia); e.g., Asian B2C e-commerce has shown growth-rates of more than 70% per year so far and other markets perform similarly [6].

To satisfy the burgeoning demand of consumption, manufacturing has to find new ways to produce and supply the needed products in sufficient number and time. Furthermore, after production, those goods have to be packaged and shipped to customers, which will substantially boost the logistics market so that logistics will be playing a key role in all areas of economy. The global logistics market is expected to grow at least 2.5 – 3% per year with an annual volume of far more than 1 trillion € at the moment [7][8].

* Dipl. Inf. (Univ.) Dominik B. O. Boesl, MBA, is with TUM School of Education, Technische Universität München, Munich and Corporate Innovation Manager and Technology Owner "Apps, Cloud & IoT" with KUKA AG, Augsburg, Germany (phone: +49-163-8435-097; fax: +49-821-8151-4282; e-mail: boesl@tum.de).

Dr. –Ing. E. h. Dipl. -Math. (Univ.) Bernd Liepert is Chief Innovation Officer with KUKA AG, Augsburg, Germany, and President of euRobotics aisbl, Brussels, Belgium (e-mail: Bernd.Liepert@kuka.com).

Combined with the current demographic developments [9] (in 2020, 50% of the German society and workforce will consist of 50+ year olds [10]), a huge potential for automation accrues. The rising request for labor can no longer be met even if the current amount of workforce would remain constant.

As the demographics hint to a dramatic shortage in available human labor (starting in Europe, spreading all over the world and climaxing after 2050, e.g., the United Nations are expecting a lack of population within Europe of about 40 million by 2060 [11]). Despite the rising population in the rest of the world, there will be a gap twice as big to fill – which unleashes unexpended potential for robot-based automation solutions. On one hand, the existing workforce has to be supported, in order to keep it capable of performing their tasks as long and as comfortable as possible. On the other hand, we will also need to support the elderly in their daily life, as humankind will not only work longer, but also live longer (the U.N. predicts an average life expectancy in the first world in 2040 of 92.4 years [11]). Keeping people active and mobile as long as possible – especially in their own home environment! - will gain more and more importance, so that investments in the field of home assisted living and elderly care or rehabilitation at home, e.g., for stroke patients, will grow accordingly. Both gaps can be filled with a 'robotic workforce'. Trends, like 'robostaffing' are meanwhile addressed even by conservative analysts and are expected to be broadly established at latest by 2025 [12].

III. SIMILARITIES BETWEEN THE EVOLUTION OF ROBOTICS AND THE EVOLUTION OF MAINSTREAM IT

The evolution of robotics and automation products in particular will be in many aspects comparable to the evolution of mainstream IT technologies. As the technological enablers drive market adoption, according to the above-explained four robotic revolutions, the pervasion and assimilation of robotics in all fields and domains of the living environment will comply with the same phases that the progression of mainstream IT-technologies followed:

Miniaturization: As computer systems evolved from room-filling mainframes into desktop PCs, robotic systems became smaller and smaller throughout the last 30 years, resulting in contemporary products like the first products in the domain of the so-called lightweight robots.

Mobilization: Transforming from desktop PCs and workstations into laptops and notebooks, computing became mobile. Accelerated by lightweight robots enabling passively mobile solutions (e.g., workers carrying a robot to the required spot on the wing of an airplane where it can perform a drilling task) and first actively mobile solutions, robotics is just at the edge of entering this phase.

Ubiquitousness: With the development of smart devices like the first smartphones, calculating power in everybody's pocket exceeded the computing performance of the first moon mission by far, putting the internet and multimedia at our fingertips everywhere and anytime. Driven by further miniaturization and better battery technologies, a multitude of ubiquitous robotic systems – first for special and later for general purposes – are evolving.

Pervasiveness: Integrated sensors, wireless communication technologies and passive ways of transmitting energy (like in RFID-chips) have put microprocessors and thus computing and networking capabilities literally in every postcard. Impelled by the Internet of Things, these pervasive systems are no longer obvious and visible for the human eye, but started to augment and interfuse everyday life. Robotics, too, will one day imbue and enrich all aspects of our living space, supporting and facilitating common tasks like shopping or automating the household.

IV. 4 ROBOTIC REVOLUTIONS

The beforehand mentioned megatrends provide a good glimpse 25 years into the global future allowing the anticipation of peoples' needs and thus the development of market developments. Nevertheless, needs and requirements alone do not lead to disruptive innovation. Only technological enablers combined with the right demand can foster fundamental change. This combination of technology push and market pull is crucial for real innovations to evolve (i.e. invention combined with market success) [13]. Over the last few years a critical mass of these technological enablers has been reached in robotics and automation. Combined with the broad availability of high-performance mainstream technologies originating from the IT domain (e.g., cloud computing, machine learning, stream analytics, fast wireless 3/4/5G communication, …), robotics is at the edge of becoming more generally accessible.

This development is also reflected in a lot of current research by well-renowned analyst companies like Roland Berger and McKinsey. In 2014, Gartner put robostaffing – robots as colleagues – on the Hype Cycle for Emerging Technologies; in 2015 they included smart robots – both technologies with an expected timeframe of less than 10 years [11]. Furthermore, they extended their holistic model of the global business environment by a post-nexus phase that is called "Autonomous Business" and will be driven and characterized by automation technology, smart robotics and expert systems [14]. This is noteworthy, because analyst companies usually target the CEOs and CIOs of global enterprises and not their research departments. This can be considered an early indicator for robotics and automation moving into the perception of a broader global audience.

Combining all the available data, innovation indicators and available technology triggers, we come to the conclusion that the evolution of robotics and automation will follow four waves, the so-called 4 Robotic Revolutions, which shall be further explained in the next few paragraphs. This phase model addresses not just robotics in particular but smart machines and automation in combination with artificial intelligence in general, thus providing a holistic view on the next 60 years of automatization, digitalization, and virtualization.

A. Robot-Based Automation Solutions

The first Robotic Revolution already happened. It is what industry has been doing for more than 40 years: Robot-based automation – or, in other words, how to bolt, weld and glue a car together as fast as possible. Some technological triggers, including progress in (micro-)electronics and IT technologies combined with other technologies enabled the evolution of the first robotic manipulators with more than three degrees of freedom [15]. These robotic arms allowed the automation of complex tasks, e.g. spot-welding, and thus laid the foundation for efficient industrial mass production. Many references name this breakthrough in industrial automation the prerequisite for the third industrial revolution that started in the 1970ies [16].

However, the robots and machines used over the last 40 years shared some main characteristics: they were fast, efficient, had high repetitive accuracy but also were very big and dangerous. This required them to be shielded off from human workers by safety fences. Like animals in the zoo, these robots were living in cages and no real interaction between man and machine was possible – either the machine was stopped to enable workers to perform service tasks or no human could safely get in close range to them while the robot was operating. Besides their limited, industry focused capabilities and safety issues, those systems were too expensive to make their way into other domains like personal robotics at home.

B. Sensitive and Safe Robot-Based Automation

The second seal has also already been broken: the second Robotic Revolution will be characterized by sensitive and safe robot-based automation solutions. Although the technologies for sensitive and compliant robotics have been broadly discussed in the research domains for many years (e.g., Khatib's early work on force-torque control & teaching by demonstration or Hirzinger's basic work at the German DLR, just to name some examples), it has only been very recently that first sensitive and safe robotic products have entered the market for industrial automation. It is important, though, to differentiate between sensitive and safe robotic solutions. Both innovations have been enabled by technological triggers in the field of sensors and control, providing feasible and affordable components to realize robots that can react to forces applied to their outer structure.

A robot that feels even slightest external forces can complete a whole set of new tasks that could not be automatized before: applying well-defined forces to surfaces, handling of non-rigid parts, collision detection, teaching by guided demonstration etc. The unprecedented breakthrough, however, lies in the intrinsic safety that can be realized with such machines. If the sensitivity is redundantly implemented and complies with the required safety regulations, such a robot can be used for direct human-machine-collaboration/ cooperation. For the first time in history, robots have been liberated from their cages and man and machine can work hand in hand – or better: arm in arm.

The impact of this very recent paradigm shift cannot really be estimated, yet. It will require a whole new way of thinking about automation solutions for industrial applications. Until now, automatization has always tried to separate human workers and machines – now we will have to think of ways how to make machines and workers coexist and even cooperate on difficult and complex tasks. These capabilities are the first step toward real service robotic scenarios. The benefit is obvious: work-assistance to make work more ergonomic and relieve the worker as much as possible.

C. Mobile, Sensitive and Safe Robot-Based Automation

The next paradigm shift will occur, when sensitive and safe robotic systems become mobile. This will, again, fundamentally alter the concepts of manufacturing and automatization, because for the first time it will not be required that the workpiece comes to the robot, but the robot will get to the workpiece. The concept of mobility is so obvious and familiar to humans, that we do not really perceive it as something breathtaking, but in robotics and automation it paves the way for real service robotic concepts.

One might argue, that there already exist mobile systems, e.g. in logistics, but these systems mostly are not safe and need to keep their distance from humans – either by playing annoying tunes the whole day, informing bystanders about their approach or by staying on separated lanes. Safe systems, though, will be able to freely roam between human workers. They will start permeating the working environment and provide their tasks so naturally, that humans will no longer think about it.

Combining these two paradigms will lead to the first true multipurpose service robots. They will still be found first in the industrial domains at first, but from there they will start spreading out to other commercial areas like retail, warehouses, supermarkets, public places like hospitals and administration buildings until they finally arrive even in domestic environments. The first field for personal robotics will be the so-called domain of home assisted living: keeping people mobile, healthy and active at home even in older years. The reason for this evolution is simple: systems will become broadly available. The more systems are produced and the further technology progresses, the lower will be the prices. But robotic systems will still be too expensive for most people to own them just for personal use. The healthcare system will help bridging this period of time: solutions for home assisted living will either be leased when needed or will be provided by the health insurance at heavily subsidized conditions. This will result in exploding demand for robotic assistive systems driven by healthcare and drastically diminish prices.

D. Perceptive and Cognitive, Mobile, Sensitive, Safe Robot-Based Automation

In the first three revolutionary phases robotic systems gain more and more capabilities, each time shifting the paradigm of how they interact with the world and with people physically. The fourth Robotic Revolution instead is driven by a paradigm change about how systems are programmed, or better, commanded. In this fourth wave, robots will start to perceive their environment, to reason based on the provided information and maybe one day even to 'understand' what they are doing.

For a very long time, automation was driven by systems that were programmed – line by line by line – to repeat more or less complex tasks at highest speed with a maximum of accuracy. Unfortunately, this one-sided optimization hindered them from becoming flexible and versatile tools. This poses a challenge for human machine interaction, because as tasks become more and more complex, programming requirements get more and more sophisticated as well. Subsequently, only skilled programmers can write the programs needed for modern automatization, whereas in the beginning even lower skilled blue-collar workers were able to use such systems by simply pushing some buttons or click programs together in very sequential scripting languages.

Therefore, the desire for perceptive and cognitive robots is obvious. Machines should understand, what their users and operators want to do, instead of being programmed to repeat basic tasks. This challenge will not easily be solved, as the level of complexity is enormous. Tasks that seem easy for humans – like a six-month old child perceiving the world by simply touching every object in its way learning their basic geometry and how to handle them – are nearly unsolvable for machines. Object recognition, for example, still is a very hard problem that requires a multitude of sensors, controlled environmental variables and very much computing power. Sure, Moore's law will help to overcome this issue with brute force, but this – within – is one reason why self-driving cars have not arrived in everyone's garage, yet.

Rosie, the Jetsons' benevolent robotic housekeeper, is still a vision of the – hopefully mid-term – future. Only, if we solve the algorithmic and computational problems of object recognition, basic reasoning and adaptive decision-making we will be able to come up with systems that will understand what we want them to do and, maybe one day, even learn like a robot-apprentice.

E. General Characteristics of the 4 Robotic Revolutions

Fig. 1 depicts a graphic representation of the four waves or robotic evolution. It has to be noted, that the waves are not mutually exclusive: even though the wave of sensitive and safe robot based automation just got unleashed, conventional robot based automation will not be replaced. The four robotic revolutions should more be considered to overlap and enhance each other: Industrial Robotics will always exist and there will be a place for the "old" kind of robots, living in cages. But new concepts, e.g. human-robot-collaboration, will enhance and enrich the working environment and start to coexist.

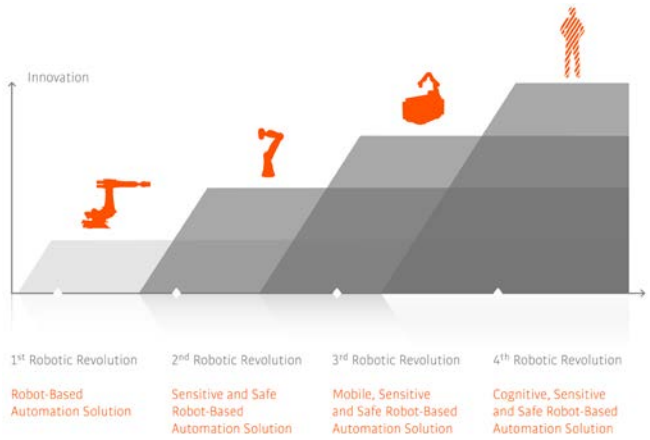

Figure 1. 4 Robotic Revolutions – Waves of Robotic Disruption

The surface under the graph can hence be interpreted as a representation for the increasing overall market volumes. Adding sensitive and safe automatization technologies, markets will at least double compare to conventional industrial robotics; adding mobile technologies, enhancing flexibility and adaptability, markets will at least double again. The same will happen as soon as perceptive and cognitive systems become available. But the different solutions from each wave will also overlap, intermingle and coexist. The differentiator between the four revolutions is the changing paradigm, which is defining their basic interaction pattern.

V. GENERATION 'R' – ROBOTIC NATIVES

Nurtured and enabled by the technological breakthroughs happening in industrial automation, robotics will permeate into other domains. In such a near-future world, where robotic systems have become commodity and help to facilitate peoples' lives, a new generation will grow up in a world that is enriched and augmented by robotics in every way imaginable. Robotics will be tailored into many everyday objects, becoming an integral part of all kinds of appliances.

"This Generation 'R' (abbreviated for Generation Robotics)…" will have no fear of direct interaction with all forms of robotic and automated systems – self driving cars, autonomous service robots, automatized logistics, robotics in retail will be perceived as normal then, as the internet, smartphones and tablets are today. "*The parallels to today's Digital Natives are self-evident […] and [h]ence, the concept […] – a whole generation growing up with iPads on their fingertips – can be transferred onto robotics"* [1].

Surely, this will not happen tomorrow, but our grandchildren will grow up as 'Robotic Natives' and will be the first Generation 'R' in the history of mankind. Analog to the term Digital Immigrant the people introduced to this world of advanced robotics at an older age might be called 'Robotic Immigrants' [1]. This "…*notion of 'native' in*

combination with modern technologies was firstly used in the 'Declaration of Independence of Cyberspace' in 1996 [17]. *John Perry Barlow states in this paper: 'You are terrified of your own children, since they are natives in a world where you will always be immigrants'. It is very well documented, that Digital Immigrants were (and some still are) deep concerned and afraid of the newly rising technologies like computers, smartphones or the Internet. In parallel, it is and will be completely normal for our Generation of Robotic Immigrants to initially perceive the same concerns and objections – as we can already experience in the actual publications or in statements like from Bill Gates, Elon Musk or Stephen Hawking. But as with the evolution of Digital Natives, these misgivings will be solved by time and become obsolete"* [1].

VI. ROBOTIC GOVERNANCE

As robotics, automation and artificial intelligence will have such a big impact on mankind in the future - comparable to the internet - we have one big chance: The Internet more or less just happened. It had never been designed to be used by a greater public audience. This explains the huge issues that arise today. Nobody could have foreseen its gigantic social and economic repercussion. Challenges, like security and privacy could have been addressed from the very beginning, but were not considered necessary.

In the case of robotics and smart machines, we can address all potential issues beforehand. We see it coming: the disruptive impact of automation on all areas of our lives will be inevitable. There will be ramifications on all levels of society, but we can address them now. In order to shape the future for our grandchildren and make robotics an enrichment and not a threat, we will have to start the structured discussion about the impact of these disruptive set of technologies today.

Robotics, automation and artificial intelligence will unleash their full power over the next five decades. If we act today, we can make sure that we are aware of the potentials as well as of the threats and act accordingly. This discussion has to be lead on all different levels: ethical and moral, socio-cultural, socio-political, socio-economical down to such basic questions as "will the robot of the future be my colleague, my friend, my apprentice, my foe or just an intelligent automatic screwdriver with two legs?"

New technologies will not only change the way we work or travel, but also our way of life. As stated before, there are many movies, newspaper articles and even scientific papers showing that people are afraid of the effects of an ongoing automation (e.g. [18], [19]). To address these fears, we have to think about implementing a framework that enables a sustainable technological development, taking into account the principle of intergenerational equity. Accordingly, a development is considered to be sustainable, if it meets the needs of today's generation, without compromising future generation's satisfaction of needs [20]. As a result, it should be the goal of the whole industry to invest in the development of technologies, that pose no potential threat for generations to come or at least address resulting risks upfront. On the contrary, robotics even offers new possibilities that foster intergenerational equity. It opens up new potentials to compensate e.g. demographic changes without reducing the quality of life.

In order to spark the interdisciplinary exchange about this topic and address the arising questions, we will need something best summed up under the notion of 'Robotic Governance' [21] [22]. This is not only an issue of taking responsibility, but also a key factor of sustainable, economic success.

From an academic point of view, Robotic Governance can be placed as a part of the economic theory of Corporate Governance. The term Corporate Governance generally means a regulatory framework for the management and control of organizations [23]. Nevertheless, it also is an assurance for the suppliers of financial means to corporations for getting a return on their investment [24]. It is supposed to surpass the legal regulation and take the interests of the different stakeholders into consideration [25]. Referring to this, Robotic Governance can be defined as a field of research, which analyzes the causes, characteristics and consequences of advances in robotics and automation as a Megatrend. It is deriving recommendations to reduce the resulting risks and analyzing the effects and interdependences for fundamental problem solving.

In principle, we would suppose, at least from a theoretical economic perspective, that market and hierarchy alone are sufficient to regulate the activities of companies. Companies that do not commit to certain guidelines are eliminated from the market. Thus, there is no need for further regulation. However, in reality, there are no perfect markets. That is why we have to limit the scope of management action by implementing laws, policies and guidelines. Otherwise, a manager will decide mostly in favor of the shareholders, without considering the interests of other stakeholders [26].

A regulatory framework can lead to a greater incentive for the stakeholders to invest in partner-specific relationships, which is resulting in lower costs of transaction [27]. In simple terms, it can be assumed, that Robotic Governance can lead to lower costs. Of course, this is not relating to costs of production or research and development but more to an economic, scientific cost concept.

Because legislation is working rather slow and only reacting to problems, Robotic Governance has to be established in the form of soft laws. Otherwise it would not be possible to achieve the goal of a sustainable development of technologies, e.g. in the field of smart machines and artificial intelligence. The traditional concept of national or international legislation is not preventing problems or risks. It is mainly focusing on a restriction of the use of technologies, that are already on the market, but potentially dangerous. And even this is limited by national borders and legal loopholes.

On the other hand, soft laws like standards or guidelines are not binding. Companies that are not obeying them cannot be sanctioned [22], [27]. Therefore, it is a crucial condition for a working Robotic Governance mechanism, to provide benefits for the companies that participate. This could be for example a better public image of a company or an increased attractiveness for investors.

The concept of Robotic Governance has been mentioned first within the Gartner CIO Summit 2013 and other events, based on the first results of a Ph. D. dissertation of one of the authors [21]. It has also been discussed by Asaro, Millar, Thomasen and Post at the WeRobot 2015 panel in April 2015 [28]. Furthermore, Robotic Governance has been focus of the 1st IEEE IROS Futurist Forum in 2015 [2] where an internationally well renowned set of speakers, including O. Kathib, G. Hirzinger and J. Heikkilä underlined the importance of addressing the topic on global scale. These efforts will be continued within the 2nd IEEE IROS Futurist Forum in 2016.

Still, Robotic Governance is a project in preliminary stages. For further enhancement, we recommend the foundation of an interdisciplinary task force that will provide the organizational framework to foster the establishment of independent, multi-disciplinary, international topic groups that can address all levels of this complex multi-layered problem. It also will be a critical success factor to attract attention and create awareness for the topic without stigmatizing new technologies. Robotic Governance should not be a limitation, but rather a tool to open doors to new and enriching possibilities for the automation industry.

VII. CONCLUSION

To put it in a nutshell, the model of the 4 Robotic Revolutions provides a compelling, holistic approach to describe the future phases of robotic evolution, characterizing them according to their technological enablers and underlying interaction paradigms.

There is no doubt that robotics will exhaustively disrupt our life over the next 50 years, as it is going to enrich and augment all domains of the human living realm [29]. Thence, our grandchildren will grow up without fear of these technologies perceiving their beneficial nature, they will grow up as Robotic Natives. In order to properly address and discuss the potential issues of automation in combination with artificial intelligence, we need a fact-based, moderated exchange about these topics: Robotic Governance.

Of course, robotics, automation and artificial intelligence are not the only disruptive technologies that will influence our society. The same debate could be conducted for e.g. cloud technology, next generation genomics or the internet of things [22].

Nevertheless, it always can be reduced to the same call to action that applies to every single researcher on this planet: In order to enable sustainable technologies and really responsibly drive "Technology for Humanity" as the IEEE claims, we all have to change the way we are thinking!

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