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Identification of new kinematic systems for laser materials processing

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Abstract

Laser-based manufacturing systems have become increasingly popular in recent years due to their ability to achieve high precision and accuracy in a wide range of applications. However, the kinematic systems used are often adapted from other manufacturing technologies like milling. These do not exploit the advantages of laser technology, e. g. the contact-free and thus restoring force-free process. A systematic search for new kinematic systems geared towards laser materials processing is carried out in accordance with the method of the technology intelligence process. The available technologies are evaluated with respect to various criteria, in particular their suitability for processing large-area components. It is determined that mobile robots should be particularly suitable for laser material processing of large-area components. The potential advantages of mobile robots are derived and discussed in a systematic method and validated with a prototype.

Keywords: laser materials processing; technology intelligence; kinematic systems; robotic

1. Introduction

Laser material processing (LMP) can be regarded as a flexible manufacturing method which, due to its high process diversity (laser cutting, laser welding, laser structuring), has already been part of established production processes for years (Hügel 2009; Poprawe 2005). Hereby, series components, but also prototypes can be produced cost-effectively and quickly (Hinke 2018; Kaster et al. 2023). To use laser technology for material processing, a relative movement between laser optics and component must be generated (Kowalick and Steffens 2011). This movement is often generated by kinematic systems adapted from other

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manufacturing processes (Kaster et al. 2023). The advantages of LMP, in particular the force-free machining of components (Hügel 2009), are not further considered. Furthermore, the paradigm applies that larger components also require larger processing machines (Dusold 2018).

However, if new kinematic systems can be identified for which this paradigm does not apply, or which take better account of the advantages of LMP, it could be possible to further increase the share of laser material processing in production processes. Since not all production processes can use the same kinematics systems, the processing of large-area components will be investigated here as a limitation. This paper is intended to answer the following question: "Which kinematic system can better make use of the specific advantages of LMP for large metal sheets?". For this reason, a systematic search for new kinematics systems for LMP is performed. The found kinematics systems are compared with each other and the best system is selected and further investigated prototypically.

2. Methods

2.1. Technology intelligence

The aim of the technology intelligence (TI) is to identify alternative technologies at an early stage and thus to draw attention to further technological development (Schuh and Klappert 2011). In particular, the focus is on identifying and observing market trends and so-called weak signals (Schuh and Klappert 2011). Technology intelligence represents an established method in the literature for ensuring technological advancement of companies and is also published under other terms such as technology monitoring, technology early warning, technology foresight or Technologiefrüherkennung (Hicking and Stroh 2022; Lichtenthaler 2002; Pfeiffer et al. 1991; Wellensiek et al. 2011). In this paper the TI method of Hicking and Stroh, 2022 is used.

There are three activities or phases for the TI method depending on the objectives set, the broadness, and the depth of search. These are, in order from more general to more specific and deep in scope: Scanning, Monitoring, and Scouting. During scanning, the entire market is observed, and information is gathered from as many information sources as possible. Then, during monitoring this newly acquired knowledge is refined and deepened, seeking data relevant to the technologies' implementation. Finally, scouting emerges directly from a well-defined already known problem or use case that needs a technology as its solution (Hicking and Stroh 2022). In the context of this paper the use case is known, the present work is considered as a technology scouting activity.

The procedure, see Figure 1, starts with the definition of the goal. Here, the search strategy and its corresponding width and depth is defined. Furthermore, the so-called search fields are defined in this step. Search fields are intended to define the information needs and narrow down the search area. According to Hicking and Stroh, 2022 up to a maximum of six search fields should be defined.

Despite narrowing down the search areas by defining the search fields, a systematic search for information (second step) makes sense. According to the literature, this systematic search can be divided into several phases. Here, the focus of the search should initially be on easily accessible sources of information such as news sites, social media and company websites. The goal is to discover new technologies and technology fields. The next step is to deepen the knowledge found. To do this, a deeper search is made in scientific literature, patents, at trade fairs and conferences, etc. for further information on the technologies already defined. (Hicking and Stroh 2022)

The aim of the third step of the TI process is to evaluate the technologies found. Various methods are proposed in the literature for this purpose, including the determination of technical readiness by means of Technology Readiness Levels (TRL). Within this work, the technologies will be further evaluated with respect to their suitability for LMP, especially with respect to the processing of large-area, planar sheet metal components. Since Hicking and Stroh, 2022 do not provide such an evaluation method as part of the process of TI, additionally the technology evaluation method of Hicking and Heimes, 2022 is used. The technology evaluation method is described in section 2.3.

The fourth step is the communication of the results. This is intended to create a basis for communication and discussion by means of a structured processing of the results in order to be able to carry out further decision-making processes systematically. The technology profile is described in the literature as a suitable tool. (Hicking and Stroh 2022)

Once the results have been communicated and a technology has been selected as suitable for further investigation, the technology is prototypically validated, and its applicability examined. If no technology is selected as suitable, the first four steps of the TI process are performed again. (Hicking and Stroh 2022)

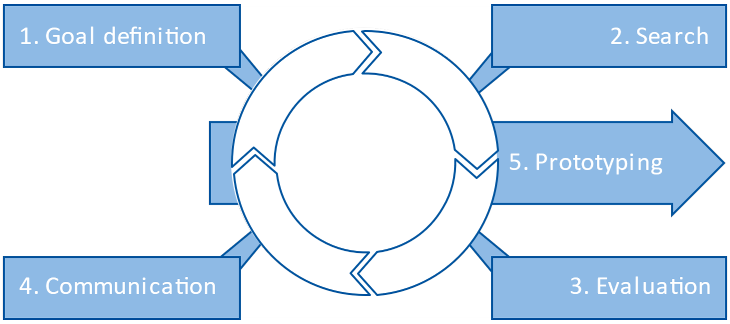

Fig. 1. Phases of technology intelligence procedure as defined by (Hicking and Stroh M. 2022)

2.2. Technology evaluation

As described in the previous section, the technology evaluation method of Hicking and Heimes, 2022 is used for this paper. The evaluation process is also divided into four steps. The first step is to define the criteria according to which the technologies are to be evaluated. These are derived from the functions that the technologies must fulfill. The defined criteria are then weighted in the second step. For this purpose, the method of pairwise comparison is proposed in the literature. Here, the individual criteria are compared directly and evaluated. If a criterion is more relevant than another criterion, it is awarded two points. If the relevance is lower, the criterion is given zero points. If the importance is the same, it is given one point. The weights w_i are calculated via the sum of the individual weights divided by the total sum of all weights of all criteria. In the next step, threshold values are defined that must at least be met by technologies. This step is not applied because all technologies, including those with low TRL, are to be searched and considered. Subsequently, the technologies found can be evaluated against each other. Here the technologies of a search field are evaluated in each case only relative to each other and not absolutely. If quantitative evaluation options are available, e. g. for the procurement price, these should be used if possible. For this purpose, a rating scale with values between 0 (worst rating) and 3 (best rating) is used. The evaluation in four different steps is intended to provide a better possibility of differentiation compared to the weighting of the criteria (three steps). The results c_i are then multiplied by the weights w_i of the criteria to obtain the overall result s_t, see equation 1. (Hicking and Heimes 2022)

$$s_t = \sum_{i=1}^{n} w_i c_i \tag{1}$$

2.3. Approach and procedure

As already described, the first step is the definition of the goal of the search. Then, the six search fields are defined. This is followed by the determination of the evaluation criteria, followed by the weighting of the criteria. Once these preparations have been completed, the search for suitable technologies can begin. Ten technologies are to be searched for each of the search fields. These technologies are then evaluated against each other using the weighted criteria. The best technologies for each search field are then evaluated against each other in a further ranking to obtain the best overall technology. For a better overview, the procedure is only carried out for one search field in this paper; the remaining results are presented in the appendix.

3. Results

3.1. Determination of the search goal

As described in the first chapter, this paper address the following research question: “Which kinematic system can better make use of the specific advantages of LMP for large metal sheets?”. So, the goal of the TI procedure is to find the best suitable kinematic system for LMP of large metal sheets, covering the specific advantages of laser technology.

3.2. Determination of the search fields

To use laser technology as a material processing method, a relative movement between the laser optics and the workpiece to be processed must be realized. This must be carried out at a defined speed on a specified path, also known as a trajectory. Various handling or kinematic systems can be used for this purpose. (Kowalick and Steffens 2011; Poprawe 2011)

Robots can be regarded as machines that are able to change their environment through predefined actions (Siciliano et al. 2009). In this respect, robots can be regarded as kinematic systems which are in principle capable of carrying out laser material processing operations. According to Siciliano et al., 2009, robots can be distinguished between mobile and fixed robots. In the case of mobile robots, a distinction is mainly made between wheeled mobile robots and legged mobile robots (Siciliano et al. 2009). However, combinations of the two types have also developed in recent years (Siciliano and Khatib 2016). In the case of fixed robots, also referred to as robot manipulator, a distinction can be made between significantly more types. In particular, articulated robots, cartesian robots and delta robots with parallel kinematics should be mentioned here (Schuh and Klappert 2011; Siciliano et al. 2009; Siciliano and Khatib 2016). Cable-driven Robots offer large scale manipulators with comparable low mass structures for their size. Through cables and winches motion can be transmitted long distances with minimal change to the robot’s mass. Current innovations in this field like advanced dynamic control schemes and sensors like the IPAnema project (Fraunhofer IPA 2014) make them a promising kinematic platforms to large scale LMP.

On this basis, the six search fields for the TI procedure can be derived. Technologies, approaches and ideas that cannot yet be assigned to an overall term due to their novelty are to be assigned to a separate search field called Non-Conventional Robots. The six search fields are: Mobile Robots, Fixed Robot Arms, Delta Robots, Cartesian Robots, Cable-Driven Robots and Non-Conventional Robots.

3.3. Definition of the evaluation criteria

To evaluate the technologies, criteria must be defined. Since the goal of the TI procedure is to find a kinematic system for the LMP of large metal sheets, sheet size must be considered here. On the one hand, the maximum processing size plays a role, but also the achievable repeatability and process speed. Since the kinematic systems must be able to support the beam guidance systems, the maximum payload plays a role. Furthermore, the costs of the kinematic systems are also relevant for later use. Finally, the laser-specific advantages should be exploited as well as possible by the kinematic systems. The evaluation criteria are thus defined as: Cost, Sheet size, Repeatability, Speed, Payload and LMP compatibility.

3.4. Weighting of the evaluation criteria

After the criteria are defined, they must be sorted according to their importance. For this purpose, the described methodology of pairwise comparison is used. The result of the pairwise comparison is shown in Table 1. To interpret the results, the column value is compared with the row values one after the other and evaluated. Here, for example, *Cost* is more important than *Sheet size*, *Repeatability*, *Speed* and *Payload*, but equally important as *LMP compatibility*.

Table 1. Result of the evaluation criteria process done by the pairwise comparison method

	Cost	Sheet size	Repeatability	Speed	Payload	LMP compatibility	Sum	Weight w_i
Cost		2	2	2	2	1	9	0.30
Sheet size	0		2	2	1	1	6	0.20
Repeatability	0	0		1	0	0	1	0.033
Speed	0	0	1		2	0	3	0.1
Payload	0	1	2	0		0	3	0.1
LMP	1	1	2	2	2		8	0.267
Total Sum							30	1

Based on the results, it can be concluded that *Cost* (first place) and *LMP compatibility* (second) are the most important criteria for the kinematic system, followed by *Sheet size* (3rd). *Speed* (4th), *Payload* (5th) and *Repeatability* (6th), on the other hand, are not very important criteria.

3.5. Result of the search for the search field Mobile Robots

Below are the results of the search for technologies in the *Mobile Robots* search field. Since the research field of robotics, and in particular mobile robotics, has developed significantly in recent years, more industrial technologies can be found here. Most of the technologies are designed for internal material transport tasks (Boston Dynamics 2022; DC Velocity Magazine 2017; KUKA AG 2022a; Mobile Industrial Robots A/S 2022; Robotnik Automation S.L. 2022; Stäubli International AG 2022) while there are, however, already approaches for material processing (Fraunhofer IFAM 2016; KUKA AG 2022b) or for the production of large 3D-printed structures (IAAC Barcelona 2022). Only one technology addresses LMP as a useful material processing technology in combination with mobile robots (Paijens 2021). The overall result of the technology search for the *Mobile Robots* search field is shown in Table 2.

Table 2. Result of the search and evaluation for the search field Mobile Robots

Ranking of the *Mobile Robots* search field										
Name	**Criteria c_i and weight w_i**									
	Cost (30 %)	*Sheet Size* (20 %)	*Repeatability* (3,3 %)	*Speed* (10 %)	*Payload* (10 %)	*LMP* (26,7 %)	Score S_t	Rank	Source
Lighthouse Guided Robot	3	3	2	1	1	2	2.30	4	(Paijens 2021)
MiR250 Hook	2	3	1	2	3	3	2.53	2	(Mobile Industrial Robots A/S 2022)
BD Stretch	2	3	2	1	3	3	2.47	3	(Boston Dynamics 2022)
KUKA KMR QUANTEC	1	3	3	3	3	3	2.40	4	(KUKA AG 2022b)
KUKA flexFEL-LOW	2	3	2	2	1	2	1.90	8	(KUKA AG 2022a)
IAAC Minibuilders	2	3	0	1	0	1	1.57	9	(IAAC Barcelona 2022)
Stäubli HelMo	2	3	2	1	1	2	2.00	7	(Stäubli International AG 2022)
CNC Mach-ining Robot	0	3	3	0	3	0	1.00	10	(Fraunhofer IFAM 2016)
Robotnic RB-KAIROS+	3	3	2	2	3	3	2.87	1	(Robotnik Automation S.L. 2022)
OTTO 1500+ Motoman	1	3	1	2	2	3	2.13	6	(DC Velocity Magazine 2017)

3.6. Result of the evaluation of technologies in the search field mobile robots

The results of the evaluation of the technologies found in the *Mobile Robots* search field are presented here, see Table 2. It can be seen that all mobile robots achieve the best rating with regard to the *Sheet size* evaluation criterion. In terms of accuracy, the technologies (Fraunhofer IFAM 2016; KUKA AG 2022b) that stand out are those that are particularly rigid due to external sensors and/or components suitable for industrial use. However, this is reflected in the costs of the kinematic systems. The *LMP compatibility* of the technologies also differs significantly, with the low-cost systems generally performing better here. The best of the technologies can be identified as the mobile robot from the company Robotnic (Universal Robots 2022).

3.7. Result of the search and evaluation for all search fields

The best technologies for each search field are listed below in Table 3. All other technologies found for all search fields can be found in the appendix. In addition to the mobile robots search field already described, ten technologies can be found for each search field. Here, systems could be identified which, in addition to material processing tasks (Universal Robots 2022), are primarily used in assembly and handling (Bosch Rexroth AG 2022; Universal Robots 2022; WEISS GmbH 2021). In addition, a cable robot for intralogistics (Fraunhofer IPA 2014) and a transformable robot (Halvorsen 2015) were identified in the non-conventional search field.

Table 3. Result of the search and evaluation for all search fields and result of the evaluation of the best overall technology

Ranking of the overall technologies									
Search field and Name	**Criteria c_i and weight w_i**								
	Cost (30 %)	Sheet Size (20 %)	Repeatability (3,3 %)	Speed (10 %)	Payload (10 %)	LMP (26,7 %)	Score S_t	Rank	Source
Mobile Robots RB-KAIROS+	1	3	2	2	2	3	2.17	1	(Robotnik Automation S.L. 2022)
Fixed Robot Arms UR20	2	1	2	2	2	2	1.80	2	(Universal Robots 2022)
Delta Robots DR4xxxC-AX050	2	0	3	3	2	2	1.73	3	(WEISS GmbH 2021)
Non-Conventional R. MorpHex III	3	2	1	1	0	1	1.70	4	(Halvorsen 2015)
Cartesian Robots 3SA Multi-Axis Syst.	2	2	3	3	3	0	1.70	4	(Bosch Rexroth AG 2022)
Cable-Driven Robots IPAnema	0	2	0	1	3	3	1.60	6	(Fraunhofer IPA 2014)

3.8. Result of the evaluation of the best overall technology

The comparison of the best technologies per search field with each other is also shown in Table 3. Here, the mobile robot from the company Robotnic (Robotnik Automation S.L. 2022) can also be identified as the best technology. The mobile robot offers the best in the *Sheet size* and *LMP compatibility* criteria compared to other criteria, at acceptable costs. Other technologies such as in the search fields *Fixed Robot Arm* (Universal Robots 2022) or *Delta Robot*s (WEISS GmbH 2021) also offer good scores in the criteria *Repeatability*, *Speed* and *Payload*. However, these were not defined as relevant to the defined goal in the technology intelligence process performed. The mobile robot is thus identified as a potential kinematic system for LMP. To check the technical feasibility, it is recommended in accordance with the TI process that this technology be investigated further by means of a prototype.

3.9. Verification of technical feasibility through the development of a prototype

The prototype of a mobile robotic system for LMP is presented below. This is built on a wooden plate and is used for the experiments, see Figure 2, left. The drive, which is necessary to generate the relative motion, consists of four omnidirectional wheels (100 mm Mecanum Wheels, NEXUS ROBOTICS LTD), which are each driven by a stepper motor (type "ST5918L2008-B – NEMA 23", Nanotec Electronic GmbH & Co. KG) with a stepper motor controller (type "drylin® D1", igus® GmbH). The movement of the mobile robot system is detected via various sensors. For this purpose, two optical tracking sensors of type "PAA5102E1-M" from PixArt Imaging Inc. are attached to the underside. These measure the relative movement between the robot and the component. In addition, a LiDAR sensor of the type "YDLIDAR G4" from Shenzhen EAI Technology Co., Ltd. is located at the highest point of the robot to determine the absolute position in the room. The sensor data is collected and processed via a Raspberry Pi 4 Model B with the Robot Operating System (ROS) distribution ROS Noetic. The calculation of the motion is also performed on the Raspberry Pi and routed to the motor controllers using an Arduino. The LMP is realized by a laser optics of the type "FiberMINI® II" from Laser Mech, attached to the back of the mobile robot.

After building the prototype, an LMP was performed. This is intended to serve as a reference process and to verify the basic technical suitability of the mobile robot system. For this purpose, a square with an edge length of 230 mm is planned and approached. The result is shown in Figure 2, right.

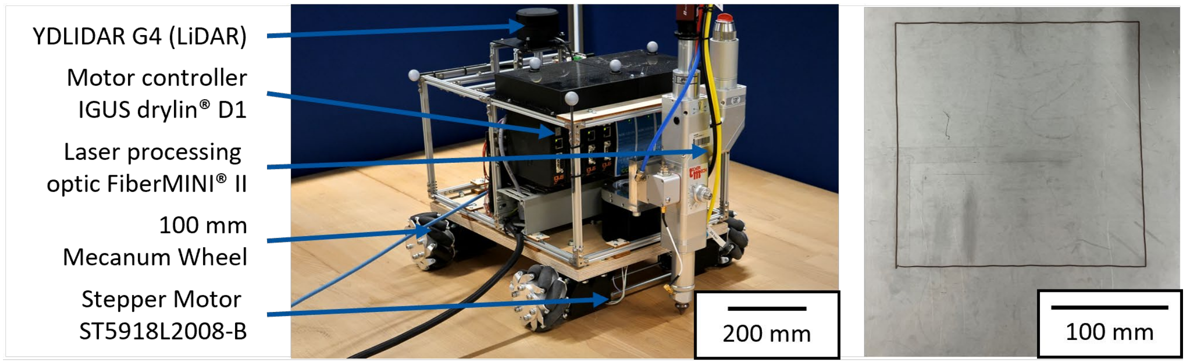

Fig. 2. left: prototype of a mobile robot system for laser materials processing incl. laser optics and sensors, right: result of an example process performed by the mobile robot system.

4. Discussion

In this section, the results are discussed. The evaluation criteria developed are tailored to the problem posed in this paper. Should a different problem be in the foreground, both the selection and the weighting of the criteria may change. For example, if the question is oriented with regard to the 3D machining of small components, the maximum sheet size probably plays almost no role. Accordingly, the evaluation of the kinematic systems found will also change and a different kinematic system could be useful.

With regard to the mobile robot systems, it can be concluded that they are very well suited for processing large-area components. This is also reflected in the results of the literature, where it is postulated that the machining space of mobile robot systems is almost infinitely large (Siciliano et al. 2009). Based on that fact it can be deduced that the size of the kinematic system no longer scales with the size of the component to be processed, which can be assumed as a principle-related advantage of mobile robot systems. This is not the case with all other kinematic systems found and offers a decisive advantage of the mobile robot systems. As a principle-related disadvantage of the mobile robot system, however, it can be assumed that, due to the small kinematics, external forces have a higher influence on the movement than with large and rigidly designed kinematic systems such as Cartesian kinematic systems. However, this plays a minor role due to the special features of laser material processing (force-free process, etc.).

Currently, no mobile robot can be identified which can already perform laser material processing as a validation option. Accordingly, a prototype of a mobile robot system is being built. Here it can be shown that material processing is possible in principle. However, the current state of development of the mobile robot system does not yet offer the possibility of processing larger sheets. The accuracy of the mobile robot system also needs to be improved. Furthermore, only one example laser process can be shown, which also needs to be further developed. However, these are technological aspects that seem to be realizable through further development (and not principle-related disadvantages). If this hypothesis can be implemented, the mobile robot systems offer significant advantages compared to the other systems found. The processing of large components is only possible with the other kinematic systems, due to the principle-related disadvantages, by a considerably higher resource expenditure (e. g. with the *Cartesian Robots*) or almost not at all (*Fixed Robot Arm* and *Delta Robots*). *Cable-driven Robots* also appear to be suitable in principle for use as kinematic systems for machining large-area components, but they have disadvantages in terms of cost and accuracy due to their prototype status. *Non-Conventional* systems also show approaches that could be further investigated.

5. Conclusion and outlook

With the approach of this paper, six search fields and ten technologies per search field could be found, which are in principle suitable for laser material processing. For comparison and evaluation of the technologies, criteria were established and weighted in order to be able to answer the question of which of the technologies found is the most suitable technology. It could be shown that mobile robot systems have principle-related advantages over the other kinematic systems. This is reflected in particular in the quasi-infinite machining area. The mobile robot system from the company Robotnic was selected as a suitable kinematic system. A prototype mobile robot system including laser optics was set up and a test trajectory was run. It was shown that laser material processing using mobile robot systems is possible in principle.

However, it was not yet possible to demonstrate a laser material processing process for large components. This will be the subject of further research work. Also, the accuracy of the mobile robot system should be improved, and further laser processes should be developed and improved.

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References

Bosch Rexroth AG (2022) Cartesian multi-axis systems for positioning and handling tasks. https://www.boschrexroth.com/en/pl/products/product-groups/linear-motion-technology/topics/cartesian-multi-axis-systems/. Accessed 8 May 2023

Boston Dynamics (2022) Stretch TM: Mobile, automated case handling for more efficient warehouse operations. https://www.bostondynamics.com/products/stretch. Accessed 8 May 2023

DC Velocity Magazine (2017) HIROTEC AMERICA Partners with OTTO Motors for Lights-Out Manufacturing with Mobile Manipulation. https://www.dcvelocity.com/articles/34365-hirotec-america-partners-with-otto-motors-for-lights-out-manufacturing-with-mobile-manipulation/. Accessed 8 May 2023

Dusold J (2018) Das sind die größten Werkzeugmaschinen der Welt: Giganten der spanenden Fertigung - Fräsen, Drehen, Bohren in XXL – PRODUKTION stellt die 15 weltweit größten Maschinen für die Zerspanung vor. https://www.produktion.de/schwerpunkte/mega-maschinen/das-sind-die-groessten-werkzeugmaschinen-der-welt-387.html. Accessed 22 May 2023

Fraunhofer IFAM (2016) CNC Machining Robot: Pressemitteilung. https://www.ifam.fraunhofer.de/content/dam/ifam/en/documents/Adhesive_Bonding_Surfaces/FFM/CNC_Machining_Robot_fraunhofer_ifam.pdf. Accessed 8 May 2023

Fraunhofer IPA (2014) IPAnema – Seilroboter für die Intralogistik: Pressemitteilung. https://www.ipa.fraunhofer.de/de/presse/presseinformationen/2014-03-20_sensorgefuehrt-und-flexibel-montiert.html. Accessed 8 May 2023

Halvorsen K (2015) MorpHex MKIII. http://zentasrobots.com/robot-projects/morphex-mkiii/. Accessed 8 May 2023

Hicking J, Heimes P (2022) Technologiebewertung: Technologiebewertung aus wirtschaftlicher, technischer und praktischer Perspektive. In: Schuh G, Zeller V, Stich V (eds) Digitalisierungs- und Informationsmanagement: Handbuch Produktion und Management 9, 1st edn. Springer Berlin Heidelberg, Berlin, Heidelberg, pp 347–371

Hicking J, Stroh M (2022) Technologiefrüherkennung. In: Schuh G, Zeller V, Stich V (eds) Digitalisierungs- und Informationsmanagement: Handbuch Produktion und Management 9, 1st edn. Springer Berlin Heidelberg, Berlin, Heidelberg, pp 329–346

Hinke C (2018) Digitale photonische Produktion. Dissertation, RWTH Aachen

Hügel H (2009) Laser in der Fertigung: Strahlquellen, Systeme, Fertigungsverfahren, 2nd edn. SpringerLink Bücher. Vieweg+Teubner, Wiesbaden

IAAC Barcelona (2022) MINIBUILDERS: SMALL ROBOTS PRINTING LARGE-SCALE STRUCTURES. https://iaac.net/project/minibuilders/. Accessed 8 May 2023

Kaster T, Ackermann M, Bailly D, Bold M-N, Bremen T, Eberius T, Fu C, Gorissen L, Haase C, Gries T, Häfner C, Heinigk C, Hinke C, Hirt G, Holly C, Kelbel H, Kolter M, Krupp U, Reitmaier L-M, Schleifenbaum JH, Schuh G, Schulz W, Stöcker L, Walderich P, Zarei O (2023) Enablers and Tools for Agile Product Development. In: Brecher C, Schuh G, van der Aalst W, Jarke M, Piller FT, Padberg M (eds) Internet of Production. Springer International Publishing, Cham, pp 1–21

Kowalick K, Steffens O (2011) System Technology: Numerically Controlled Tooling Machines for Laser Materials Processing. In: Poprawe R (ed) Tailored Light 2: Laser Application Technology. Springer Berlin / Heidelberg, Berlin, Heidelberg, pp 427–472

KUKA AG (2022a) flexFELLOW: KUKA flexFELLOW: the flexible automation concept. https://www.kuka.com/en-de/products/mobility/mobile-robots/kuka-flexfellow. Accessed 8 May 2023

KUKA AG (2022b) KMR QUANTEC: KMR QUANTEC: autonomous and precise. https://www.kuka.com/en-de/products/mobility/mobile-robots/kmr-quantec. Accessed 8 May 2023

Lichtenthaler E (2002) Organisation der Technology Intelligence: Eine empirische Untersuchung der Technologiefrühaufklärung in technologieintensiven Grossunternehmen. Zugl.: Zürich, Eidgenössische Techn. Hochsch., Diss., 2000. Technology, innovation and management, vol 5. Verl. Industrielle Organisation, Zürich

Mobile Industrial Robots A/S (2022) MiR Hook 250. https://www.mobile-industrial-robots.com/solutions/mir-accessories/mir-hook-250/. Accessed 8 May 2023

Paijens AFM (2021) Localization of Mobile Robots for Precision Manufacturing, Auckland University of Technology

Pfeiffer W, Metze G, Schneider W, Amler R (1991) Technologie-Portfolio zum Management strategischer Zukunftsgeschäftsfelder, 6th edn. Innovative Unternehmensführung, vol 7. Vandenhoeck und Ruprecht, Göttingen

Poprawe R (2005) Lasertechnik für die Fertigung. Springer-Verlag, Berlin/Heidelberg

Poprawe R (ed) (2011) Tailored Light 2: Laser Application Technology. RWTHedition Ser. Springer Berlin / Heidelberg, Berlin, Heidelberg

Robotnik Automation S.L. (2022) RB-KAIROS+ MOBILE MANIPULATOR: RB-KAIROS+ is presented as a solution for Universal Robots e-Series users. https://robotnik.eu/products/mobile-manipulators/rb-kairos/. Accessed 8 May 2023

Schuh G, Klappert S (eds) (2011) Technologiemanagement: Handbuch Produktion und Management 2. Springer Berlin Heidelberg, Berlin, Heidelberg

Siciliano B, Khatib O (eds) (2016) Springer Handbook of Robotics, 2nd edn. Springer Handbooks. Springer Berlin Heidelberg, Berlin, Heidelberg

Siciliano B, Sciavicco L, Villani L, Oriolo G (2009) Robotics. Advanced Textbooks in Control and Signal Processing. Springer London, London

Stäubli International AG (2022) Mobiles Robotersystem HelMo. https://www.staubli.com/global/de/robotics/produkte/mobiles-robotersystem.html. Accessed 8 May 2023

Universal Robots (2022) INTRODUCING THE UR20: This is the cobot. Redefined. https://www.universal-robots.com/products/ur20-robot/

WEISS GmbH (2021) DR Delta Robots: Breathtaking speed. https://www.weiss-world.com/gb-en/products/robots-10327/delta-robots-211. Accessed 8 May 2023

Wellensiek M, Schuh, Günther, Hacker, P. A., Saxler J (2011) Technologiefrüherkennung. In: Schuh G, Klappert S (eds) Technologiemanagement: Handbuch Produktion und Management 2. Springer Berlin Heidelberg, Berlin, Heidelberg, pp 89–170

Appendix A.

Supplementary Information and the remaining results of the search technologies for all search field can be found under the following link: https://s.fhg.de/kaster2023a