Artificial Intelligence in 3D Printing

Real-time 3D printing control

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Abstract:
Artificial Intelligence (AI) is the leading field of science nowadays. Machines can learn and complete tasks independently. Additive manufacturing (AM) is still a developing technology. However, 3D printing is much more than the production of plastic prototypes. The latest technologies of artificial intelligence and additive manufacturing are reviewed in this thesis. The most developed and reliable technology is stereolithography (SLA) in 3D printing. Therefore, SLA 3D printing process has been taken as a basis for studying the interaction between artificial intelligence and additive manufacturing for finding and solving problems in the production process. Imperfections of SLA are identified due to the visiting Ajatec factory where rapid prototypes and small batches of products are manufactured with stereolithography. Stereolithography manufacturing and design processes are described based on the literature and practical experience. Photopolymer materials and photopolymerization reaction are reviewed as well. Solutions, for achieving the control over the different parts of the SLA process, are presented and carefully organized with algorithms and plans. Ajatec company can use this knowledge to start various projects associated with the optimization process of the real-time 3D printing control. Possibilities and prospects are discussed to give an understanding of the significant importance of AI with AM for the nearest future.

Keywords:	Artificial Intelligence, Additive Manufacturing, Stereolithography, Photopolymerization, Machine Learning, Real-time 3D printing control, Ajatec company
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Abbreviations

AM	Additive manufacturing
SLA	Stereolithography
FDM	Fused deposition modeling
CAD	Computer aided design
CAM	Computer aided manufacturing
UV	Ultraviolet
CT	Computed tomography
DNA	Deoxyribonucleic acid
IPN	Interpenetrating polymer network
PLA	Polylactic acid
ABS	Acrylonitrile butadiene styrene
AI	Artificial intelligence
ML	Machine learning
DL	Deep learning
VAT	Tank bath
CNC	Computer numerical control
PEI	Polyetherimide
IT	Information technology
STL	Stereolithography file format
3MF	3D manufacturing format
VRML	Virtual reality modeling language

List of symbols

C	Carbon
H	Hydrogen
O	Oxygen
N	Nitrogen
Cl	Chlorine
F	Fluorine
B	Boron
P	Phosphorus
Si	Silicon
E_c	Critical exposure
E_0	Energy amount on the surface
C_d	Curing depth
D_p	Penetration depth
ε	Molar extinction coefficient
I	Photoinitiator concentration
ε_I	Extinction coefficient
ε_A	Extinction coefficient
A	Concentration of the absorber
E_x	Excess energy

1 INTRODUCTION

1.1 Background

The history of plastic materials industry started from 1868 when John Wesley Hyatt have been trying to search for a new material for billiard balls and discovered cellulose. The company called Akerwerk made the first type of injection molding machine in Germany in 1950 (Mastro, 2016). Evolution of the manufacturing industry happened when plastics replaced other materials. Nowadays, plastics are multifunctional polymers that can be modified easily with modern technologies for various applications.

Monomers are combined to form a polymer during the polymerization process that identifies future properties of the polymer. Thermoplastic is a polymer that becomes elastic above a certain temperature and solidifies after cooling. Polymer chains can move in thermoplastics while heated, but in thermosets, polymer chains are locked due to the cross-linking reaction and cannot be easily modified after the hardening of the polymer.

1.1.1 Additive manufacturing

Additive manufacturing is the most prospective and highly evaluated technological field in the modern world. 3D printing technologies take an origin from the Stereolithography printing technique which has been invented in 1984 (Attaran, 2017). Additive manufacturing is used to create objects with complex shapes which are not possible to manufacture with traditional techniques. AM develops evolution of science with rapid prototyping and digital manufacturing. Various polymer, metal and bio materials are used in engineering applications mainly to create prototypes and finished products with unique shapes, multifunctional compositions, reliability and high quality.

The future will be different due to the development of AM technologies. Innovations will lead to the shortening of the supply chain which means that consumers would be able to print anything they want at home and on remote. Digital manufacturing era just started, ideas can be transported to the 3D models and then send directly to the 3D printing machine that can start work and finish without human supervision. The only thing that people will care about is the different materials for production of food, equipment, products for replacing broken parts, etc.

Moreover, technological development will make consumers as home manufacturers and this exciting opportunity will bring infinite freedom to small businesses and private consumers against monopolist corporations. If the possible feature is to produce everything including essential things at home, then there is no need in buying products.

1.1.2 Artificial intelligence

Artificial intelligence and software development are the main fields of future jobs and consumer market (Raftery, 2017). In general, the familiar market should change to the world digital market.

In order to reach this magnificent future, countries should unite their local additive manufacturing markets and cooperate on developing and distributing 3D printing technologies around the world. United Kingdom, United States and most of the leading European countries are entering the digital manufacturing era. For example, "Airbus" company uses most of the parts for airplanes designed and manufactured with AM (Attaran, 2017). Almost all engineering materials are working in AM field too. Bridges are started to be constructed with robotic 3D printers in Netherlands. Specific athlete shoes are partly made with AM technologies in US. There are a lot of examples how 3D printing technologies have been already implemented in ordinary life.

1.2 Objectives

The main target of this work is to describe interaction between artificial intelligence and additive manufacturing, especially in SLA 3D printing with photopolymerization reaction process, for achieving real-time 3D printing control. Combination of AI and AM should improve manufacturing process and develop new technologies. Therefore, concept of AI science with subfields is described with the support of the newest technologies and opinions of leading AI specialists. Moreover, SLA 3D printing manufacturing problems are presented and discussed in this research. The aim of the method is to develop planned solutions for various problems. These plans should be implemented for the future projects to improve the real-time 3D printing control. Manufacturing failures have been identified and formulated after the visiting "Ajatec" digital manufacturing company.

- Describe relation between AI and AM.
- Explain the concept of the AI working system.
- Create algorithms for control over the 3D printing properties.
- Represent the required human resources.
- Introduce the necessary equipment.

1.2.1 Problem of the research

Failure during the SLA printing process. Failed print, must be recycled, and the process is repeated creating a lot of material and financial resources waste.

1.2.2 Research question

How to fix the failure during the SLA printing process without interruption?

1.2.3 Relevance of the problem

The research is extremely relevant now, because the development of machine learning can significantly improve additive manufacturing process in the following ways:

- Manufacturing process efficiency would rise to 100%.
- Product failure during the production process would be excluded.
- General probability of the product failure would be reduced.
- Zero waste manufacturing.
- Production and waste control cost reduction.

- Significant increase of income from production.
- Product quality improvement.
- Discovery of the technology that can be patented.
- Bringing SLA manufacturing to a new level.

The objectives are very ambitious. Products will be made always successfully. No material waste, no risks of failure. New generation of quality. All problems will be detected and fixed on the earliest stage directly during the manufacturing process.

The topic is significantly relevant for the all parties, because the additive manufacturing technology improvement leads to the development of science, production technologies, and also increasing of the educational level, since students use 3D printing for the projects and research works.

1.2.4 Relationship to existing knowledge

SLA 3D printing process is the oldest and time-tested technique, which can be improved by the implementation of the newest machine learning and artificial intelligence knowledge. The work is focused on the concept of combination of AM and AI to control 3D printing process properties and improve achievements of the previous researchers and innovators.

This is a great possibility to work on the problems of the stereolithography with implementation of AI, since there are only few similar researchers going for other AM techniques, which makes this study unique.

1.3 Scopes and limitation

This research is about combination of artificial intelligence and additive manufacturing. However, only SLA 3D printing process is the main focus of this research, therefore photopolymers and photopolymerization reaction are described in detail. This printing process is the oldest and the most accurate one which has high quality products used in medical field, jewelry production and high-tech engineering applications.

Problems that project will meet, ascending difficulty:

1. Deep studying of very specific scientific problems.
2. Innovating solutions and concepts for various failures in the SLA 3D printing process.
3. Developing a scanning system.
4. Creating an AI system.

2 LITERATURE REVIEW

The presented literature covers various parts of the research including additive manufacturing, artificial intelligence and SLA 3D printing process. Moreover, interaction between these fields is introduced based on the modern technologies and the latest research studies. This literature is needed to support the method plans and solutions.

2.1 Additive manufacturing processes

3D printing technology has been used as a rapid prototyping technique for a long time. The main functional application of the 3D printing was in the field of industrial and manufacturing use. 3D printing machines were mainly implemented for the rapid manufacturing of plastic prototypes in the past (Kerns, 2018).

Significant development of the additive manufacturing technologies for the last years happened in the field of industrial applications for the manufacturing of the functional finished products. However, the first advantages of the 3D printing processes are still playing significant role in the development of AM technologies and implementation of these techniques in the market. 3D printing is the best choice for rapid prototyping considering high speed manufacturing complete prototype with the mechanical properties of the plastics polymer materials used. The results of prototyping are close to industrial, ergonomics, aerodynamics, etc. The modern 3D printed prototypes meet the requirements and completely match the properties of the final functional model produced with traditional manufacturing methods (Kerns, 2018).

The most popular AM techniques according to (Bourell, et al., 2017):

- Directed energy deposition (DED)
- Binder jetting
- Material jetting
- Material extrusion
- Powder bed fusion

- Sheet lamination
- VAT (tank bath) polymerization

2.1.1 Direct energy deposition

Direct energy deposition technologies include principles where fusion energy and material are transferred in the same time to the building place of the part. 3D printers have the system which transports the material and the energy focused by the laser beam (Peels, 2017).

3-dimensional object is formed and sliced in many layers. Next, powder material is applied to the working surface with the thin layers. Laser beam fuses powder material on the chosen patterns according to the G-code which represents coordinates for movement of the laser beam. In cured areas powder melts and solidifies. The process repeats with the lowering of the build platform exactly on the one printing layer. When the printing is finished then the product is taken from the working space and cleaned from the remaining powder (Peels, 2017).

2.1.2 Binder and material jetting processes

Binder and material jetting processes have many similarities, but there are some distinctions too. Binder jetting uses the principle of printing object through the nozzles of the extruder with the spraying of the connecting element on the surface of metal, polymer or plaster (Josten, 2017). Material jetting transfers building material through the nozzles that solidifies after applying to the surface (Varotsis, 2018).

Building chamber of the 3D printer consists of two parts: The first one where the building material is filled, and the second part is the space for the printing process (Varotsis, 2018).

There are several stages of the jetting 3D printing (Michalik, et al., 2015):

- Designing digital 3D model.

- Applying the thin layer of the powder on the build plate.
- Jetting the binder material on the borders of the model first layer.
- Platform lowers one level down and camera with the binder lifts one level up.
- The next layer is rolled on the platform.
- Post processing of the model requires cleaning of the powder.

There are some advantages and disadvantages of the jetting 3D printing. Positive sides include excellent printing speed and the low cost of the consumables (Varotsis, 2018).

Negatives consist of objects made from plasters, which are quite brittle, and this fact limits the application, only disposable molds and plaster material that produces a lot of dust (Varotsis, 2018).

The jetting technique is applied in different fields. Most of them are quite common, but among others there are some special ones such as bio-printing and confectionary production. Organic tissue is created by spraying the living cells layer by layer (Kesari, et al., 2004). Confectionary uses jetting for decoration of their products forming the 3D objects made from sweet materials. Material is usually a plaster, but different types of plastics can be used and even metals. However, these materials should be in the suitable powder state (Bourell, et al., 2017).

2.1.3 Material extrusion

Material extrusion includes one of the most popular and affordable 3D printing technology which is fused deposition modeling (FDM). Plastic material in a form of the filament is attached to an extruder where the material melts forming a line coming out from the nozzle. Melted plastic is extruded in a linear form creating a printing level and thermoplastic immediately solidifies after touching the surface of the build platform or a previous printing layer. Each layer is built on the previous one using supports if needed forming a 3D dimensional product. Nozzle moves in two-dimensional space while the build platform is lowering every time when the printing layer is finished (Bourell, et al., 2017).

Models produced by FDM technology are impact resistant and functional. Manufacturing industries use FDM to create prototypes, check and adjust the tolerance of the final product. FDM technology is mainly used for simple applications in educational institutions, domestic modeling, basic prototyping and creative art products (Ligon, et al., 2017).

2.1.4 Powder bed fusion

Powder bed fusion is based on melting the material in the prepared printing layer beforehand or in serial forming of the powder layers fusing selectively parts of the building material. Powder is rolled by the special roller on the build platform installed in isolated space with inert gas inside. The laser beam shoots the programmed patterns on the building material. The laser beam is the source of energy which is transferred to the powder to fuse small parts of the material. Next, the platform is lowered down by the distance equal to the thickness of a single printing layer. The new powder layer is rolled on top of the previous layer and the laser shoots again, but with the new pattern which is usually slightly different from the previous one. Both layers are fused. The process continues before the part is finished. Powder bed fusion does not require any supports since the powder surrounding the product works as a support itself. The model is removed from the powder container and the product is cleaned from the remaining powder (Sun, et al., 2017).

Powder bed fusion 3D printers are able to build large objects without assembly process. This an important feature for accuracy of the casting and reliability of the model, especially in the vacuum casting. Casting of wax or polystyrene models are not that different, but the main difference is that wax can be melted inside while thermoset can only be burned. Thermoset while burned produces gases causing a dangerous effect of forming the ash and dirt in the casting mold. Channels for trickling of the burned and melted material should be created to avoid formation of the stagnant zones. Thermosets are cured in the calcining furnaces beforehand. These technique gives quite good results if experienced person uses the casting method (Locker, 2018).

However, temperatures in the powder are different during the printing process which creates a possibility of the heat deformation. The model needs careful and accurate post processing (Locker, 2018).

2.1.5 Sheet lamination

Sheet lamination includes technologies which uses material in a form of polymer films, paper sheets, metallic foil, etc. Some technologies are utilizing thin metal sheets welded together with ultrasound and then remaining unnecessary material is removed with the computer numerical control (CNC) technique. Some sheets are attached together with specific adhesive or with the fasteners such as bolts and rivets. One of the first additive manufacturing technologies used in the manufacturing industry utilized special paper with the polymer coating. Heated roller fuses each layer of the coated paper on top of each other. The unnecessary parts of the paper are separated from the important pattern by the laser beam. Moreover, cuts are made in the process to simplify removing of the object from the surrounding material (Silbernagel, 2018).

2.1.6 VAT polymerization

VAT polymerization is an additive manufacturing technology which uses photopolymer materials cured by the ultraviolet (UV) laser beam. Photopolymer receives energy activating electrons in the initiators reacting with the functionals groups starting polymerization process. Polymer chains are formed in the network form clinging to each other. This technology has a high surface quality which is used in prototypes, medical industry, jewelry for casting and stomatology for creation of accurate mouth guards (Varotsis, 2018).

2.1.7 Prospects and advantages of AM

Additive manufacturing is a young technology compared to traditional manufacturing methods. There are a lot of possibilities for improvement of this technology. Increased quality of the machine components will improve 3D printing, and innovations should lead to better results in printing speed, optimization of the design process and movement of the toolpath. One of the main targets for engineers is to achieve the increasing printing speed for large object (Lipson & Kurman, 2013).

The best advantage of the 3D printing is independent and unsupervised production of complex shapes. However, common problem of the 3D printer is the size of the printing object. Large objects are divided into small parts that should be assembled together. This solution leads to a prolongation of the workflow (Tofail, et al., 2018).

Private companies and government are investing financial resources in the development of additive manufacturing with realization of its potential for economical grow. Cost of 3D printers will be reduced to make this technology affordable for customers. Also, 3D printing companies are trying to find the way how to reduce filament cost. General cost of the software, 3D printers and filaments will be reduced, and individual consumers will be able to access the 3D printing market. This situation will significantly simplify the supply chain with the need of shipping only equipment and filament. Quite many things would be possible to produce at home with the additive manufacturing (Tofail, et al., 2018).

For instance, broken parts could be replaced by home printed products, user would need only to download the required design. Moreover, AM parts have a good quality for aerospace, medical equipment, prototyping, etc. 3D printing technology produces little waste compared to other manufacturing methods which improves sustainability. AM could work in zero gravity to produce goods and food for astronauts, bearing in mind expensive delivery of the things in space (Attaran, 2017).

3D printing has taken almost the whole prototyping market for architecture. Some houses are quickly build for solving poverty problems in warm countries. There are going to be a lot of possibilities with the development of additive manufacturing technologies in the nearest future that society cannot even imagine (Attaran, 2017).

2.1.8 AM technologies in automotive industry

Additive technologies are widely used in the automotive industry nowadays. AM is often associated with supporting technological processes such as making master models and molds for casting small batches of products or prototypes. However, 3D printing becomes more confident as the basis for the manufacturing of the functional products (Attaran, 2017). Porsche company, as the Leading German manufacturer of the first-class vehicles, started to use 3D printing technology to manufacture parts for rare classic cars. AM technologies are the most accurate manufacturing techniques that can produce complex detailed parts with unique shapes very close to any wish of the designer. There is no such a technology that can rapidly make so much detailed products with the same quality and speed ("Porsche Classic Supplies", 2018).

There are more than 52,000 parts in the Porsche Classic cars. There is a need of special equipment in case of the spare part failure for the original series. Creating special tools is unreasonable in quite expensive for the small series while the designing of special equipment is advisable for large batches ("Porsche Classic Supplies", 2018).

Porsche has added to its collection different spare parts manufactured with the additive manufacturing method. Combination of SLM for the manufacturing of metal parts with SLS for plastic parts and special equipment is used representing perfect implementation of the 3D printing technology for specific need ("Porsche Classic Supplies", 2018).

Car manufacturers are increasingly utilizing 3D printing implementing AM techniques for the production of the interior parts, structural elements, accessories and spare parts. Volkswagen saves more than 160 thousand of dollars annually due to the usage of 3D printed components in the factory assembly line ("Volkswagen Uses The Latest", 2018).

Digital Spare-Part Initiative project has been launched by the Mercedes-Benz Trucks which is based on the initiative to create spare parts with digital manufacturing technology. SLS technology has been used by Daimler Trucks company for a long time to produce spare parts for its vehicles ("Premiere At Mercedes-Benz", 2017).

3D printing is used during the process of assembly and production of a new generation SUV by the famous creator of the automobile Ford conveyor company. Ford Escape and Lincoln MKC broken parts are replaced with significantly less time using AM methods than with traditional manufacturing techniques ("Ford Tests Large", 2017).

2.1.9 Regulation for the individual use of AM technologies

Regulation system has been implemented for additive manufacturing a long time ago since there was an opportunity to produce parts from metal and composite materials without control. Cody Wilson designed and produced with 3D printing technologies a plastic gun that cannot be identified by the metal detectors in 2013. Design has been available for free, but the file was banned after a short period of time due to the public safety reason. Nowadays, government decides which company can get the license for printing metal parts and what individuals can print (Jackson, 2018).

There are a lot of things that small company can do with 3D printing technology. For example, product prototypes for car manufacturers help to save money, but having own designers is so expensive, therefore companies prefer to pay few times using outsourcing company. Also, there is an opportunity to make an actual mold for casting and the product prototype to check the tolerance, appearance, functionality, etc. Manufacturer prefers to lower the risk, in case that new product parts do not fit together. 3D printing company scans an expensive damaged part of the machine, reestablishes design, rents specific 3D printer and then prints the part. The main field of the income for 3D printing business are custom parts in the medical industry, vehicle manufacturing, jewelry and commercial airplanes companies. Business can even start from an individual workshop by using home affordable printers (Lipson & Kurman, 2013).

2.2 3D printing materials

Plastics are the most common materials for 3D printing technologies. Polymers are applied for everyday needs as insulation, packaging, simple tools, etc. On the other hand, complex plastics that have been modified for specific engineering reason cost more than metals. Additives improve basic properties of the plastic materials and increase their cost. For example, plastic parts degrade under the influence of sun light that is why UV light protection additive is widely used in manufacturing of plastic products. Medical healthcare companies prefer their products to have antimicrobial additive. Each additive solves specific problem that makes plastic materials unique (Bourell, et al., 2017).

Important material properties for 3D printing according to (Mastro, 2016):

- Melt flow index/Melt flow rate is a characterization of the polymer flow when melted (grams/minute).
- Crystallinity presents how polymer chains are formed together into one structure.
- Thermal properties of plastics depend on glass transition temperature and melting temperature.
- Thermal conductivity properties of the plastic can be modified with addition of fillers.

Price of the plastic material depends on the cost of raw material, polymerization process and the final amount of produced material. Natural resources such as natural gas, coal and petroleum are used for production of plastics. Each country has different resources that identifies what is going to be used as material for polymerization (Bourell, et al., 2017).

Material has an important role in 3D printing. Material should be in suitable state for specific manufacturing technology: liquid, powder, filament, etc. Each manufacturing method requires specific material properties. Moreover, material should be able to work in specific environmental conditions and withstand the loads to meet the application requirements. Post processing improves physical properties of the product such as microstructure and surface roughness (Bourell, et al., 2017).

Experience of working with additive manufacturing technologies has identified certain types of materials suitable for production according to the latest 3D printing trends published by 3D Hubs company (Fisher, 2018).

2.2.1 PLA

Polylactic acid (PLA) is a biodegradable polymer material which is often used in FDM printers as a filament. This thermoplastic is made from natural plant elements such as sugar cane, soy protein and cellulose. These natural raw materials make PLA unique allowing usage for different applications without hazardous consequences for the human health. Moreover, production of PLA has much less carbon emissions compared to manufacturing of polymers based on the natural oil. The amount of natural resources for production of PLA can be reduced and the process does not require any solvents. However, polylactic acid is a brittle material which requires careful post-processing. Also, one disadvantage related to the fragility, material degrades with time by microbes. PLA has time limit of usage from several months to few years (Bourell, et al., 2017).

This material is perfect for 3D printing of rapid prototypes, decorations and presentations. PLA has high quality of detailed parts with a short existence time. Material properties include (Södergård & Stolt, 2002):

- Melting temperature range 130 – 180 °C.
- Tensile strength 2.7-16 MPa.
- Glass transition temperature 60-65 °C.

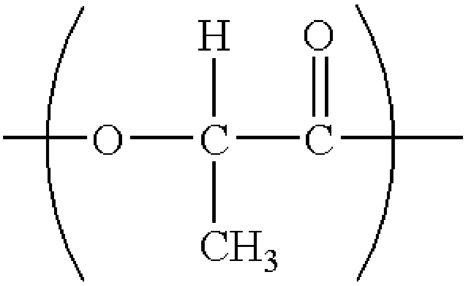

Figure 1. Polylactic acid and manufacturing process thereof (Kimura, et al., 2005).

2.2.2 ABS

Acrylonitrile butadiene styrene (ABS) is an impact resistant polymer which is widely used in prototyping and industrial manufacturing. This thermoplastic does not have the same quality of details as PLA, but ABS is more practical and can be used for manufacturing of functional products. ABS has been implemented for the FDM 3D printing and material comes in a form of the filament. ABS plastic is quite safe, and this material does not have a human threat in normal conditions. However, the heating of ABS leads to vaporization of toxic acrylonitrile. Basic safety rules must be applied must while working with acrylonitrile butadiene styrene in 3D printing. The evaporation is not that significant due to the relatively slow consumption of material during FDM printing. To ensure a completely safe environment, only good ventilation and extraction are required. One important feature is that ABS plastic reacts with ethanol, which results in the release of styrene (Rogers, 2015).

Also, ABS material has a high rate of shrinkage which leads to surface and volume deformations. Therefore, product made from this thermoplastic should be post processed with vapors of acetone to make the external surface smooth and shiny (Bourell, et al., 2017).

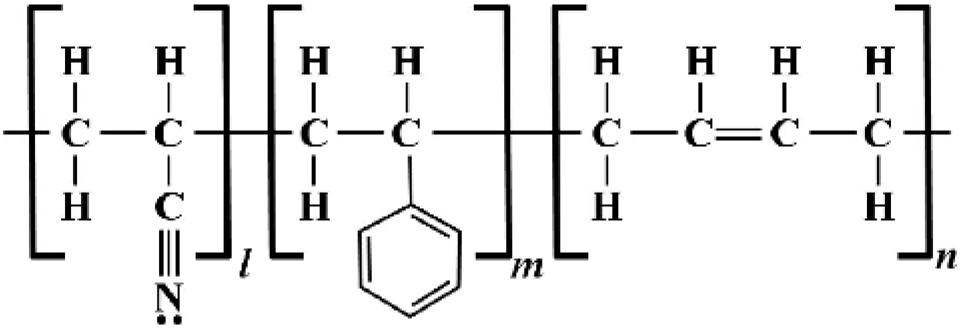

Figure 2. Acrylonitrile butadiene styrene (Faudree, 2016).

Material properties ("This Data Represents Typical", 2018):

- ABS plastic does not have exact melting point, but 240 °C is used as a standard for 3D printing.
- Tensile strength 52 MPa.

2.2.3 Standard resin

The most typical 3D printing material is a standard resin since the beginning of additive manufacturing. This thermoset has been developed for SLA 3D printing process and first the material came as the photopolymer consisting of monomers, oligomers and photoinitiators. Products have high quality detailed parts and smooth surface. The material is widely used in medical field, jewelry and rapid prototyping. Also, standard resin is much more flexible than other plastics becoming unique and multifunctional for various applications. Moreover, this type of material can be often transparent (Molitch, 2016).

Material properties according to (Latouche, 2018):

- Resin is a thermoset that can work with temperatures above 200 °C.
- Tensile strength 65 MPa.

2.3 Product Design

2.3.1 CAM and CAD

Originally AM was created for prototyping to improve the process of transferring the idea to the 3D model and then to the physical object. Two main components are used to create design for 3D printing: Computer aided design (CAD) is created to design the 3D object and save the model as the digital file. The same data set is used by computer aided manufacturing (CAM) software which calculates moving path of the printing head (Hultgren, 2018).

2.3.2 Tolerance and clearance

Some parts do not fit each other because of the tolerance and clearance. Tolerance is permissible variation of the part. This characteristic is defined as the range of various numbers. Clearance is an established number for the space between mated parts. There are many gauge test files publicly available online that can help to check tolerance and clearance of any 3D printer (Hultgren, 2018).

2.3.3 Build plate

For some engineers the build plate is an obvious part of the printer, but for others this part is a not so familiar. Printing of the model requires a build plate. The most essential part in this situation is how the printing sample is attached to the plate. There are some examples of features for build plate adhesion that can significantly improve the 3D printing process and exclude possible printing failures (Hultgren, 2018):

- Skirt is a single layer of material printed around the part without touching the surface of the model. Usually skirt is used to adjust printing settings in the begging of the printing process.
- Brim option consists of multiple material layers printed around the part touching the edges of the model to hold these edges causing anti warping effect.
- Raft feature works as a basement that supports details of the upper levels of the part. Also, raft is often used for stabilization and to prevent warping.

Printing plate is the base for the printed model. Plates are usually divided in two categories: heated or unheated (Hultgren, 2018).

Heated plates are usually hot or cold. Plate made from the metal is often covered with tape, glass, PEI (polyetherimide). Various materials to work with is a positive side of these plate type, on the other hand heating or cooling process takes a lot of time (Hultgren, 2018).

Unheated plates are disposable and reusable. Disposable plates are built on purpose with opportunity to work with different thermoplastics, however these plates are quite expensive (Hultgren, 2018).

Reusable plates are usually made of glass, plastic and metal. This type of plates works well with PLA and ABS. Thin glue layer or tape are used for surface treatment. No heating is required for reusable plates. This feature lowers the cost and saves time (Hultgren, 2018).

However, the knowledge about build plates is essential for this case, but the most important thing is how to use and adjust the build plate to compensate the failure during the printing process for this research.

2.3.4 Design process

Manufacturing process includes several parts according to (Hultgren, 2018):

First, the idea is designed as a 3D model and the digital file converts to the G – code for the printing process. This code is an instruction that 3D printing software can work with to send the command for movement of the printing head and heating or cooling the build plate. The path of the tool, which jets, fuses or transports material in any other way, can be easily observed in the slicer program (Hultgren, 2018).

For instance, Formlabs SLA 3D printers has the PreForm slicer software which works with imported CAD files and STL assemblies. This program is used to optimize 3D printing process. PreForm prepares 3D print and shows the print preview with estimated processing time ("PreForm Prepares Your", 2018).

Common CAD file formats (Hultgren, 2018):

- Stereolithography (STL)
- 3D manufacturing format (3MF)
- Virtual reality modeling language (VRML)

Custom settings are used by experienced machine operators. For example, type of the infill structure, raft, base and other printing parameters are modified in custom settings.

PreForm preview function shows how the 3D model is printed layer by layer ("PreForm Prepares Your", 2018). Preview is also useful to check how changes in settings is affecting on the printing process. Another interesting option to check the printing process is to use G – code web analyzer which is created for animation sequence of layer printing. This open source software shows printing speed, time, amount of material used and height for each layer ("GCodeViewer Is A Visual", 2018).

Models with complex shapes require supports and knowledge of printing rules. Common practical advice: try not to print objects with overhangs beyond 45 degrees, otherwise the process leads to a failed print (Hultgren, 2018). Concerning supports, two types are used in the printing process (Hultgren, 2018):

- Removable supports use same material that is usually removed manually with tools.
- Supports made from the different material other than the build material are dissolved in the chemical bath in the post processing.

There are many ways how to print the object without supports to reduce cost, save time and material (Hultgren, 2018):

- The right choice for orientation of the part reduces amount of support material and improves physical properties. Printing lines should be perpendicular to the stress.
- Bridges connect two sides of the part filling the gap in the air. This feature excludes support material in some cases.
- Custom support with chamfers and fillets are often used to avoid supports in complex designs.
- Almost every model can be cut into small pieces. This separation simplifies managing of the printing process.

Infill of the printed models usually varies from 10%-50% for rapid prototypes. Functional part has more than 25% of the infill while prototype, which is designed for visualization or decoration, use less than 15% of the infill (Hultgren, 2018).

If the main printing target is to improve strength, then increase of the infill and more shells should be added. Opposite actions decrease printing time. These properties are changeable and should be tested in the slicer software to find the best value before the actual 3D printing process. However, functional parts are not that difficult to print compared to the functional assemblies (Hultgren, 2018).

Printing an assembly is not an easy task. There are several observations simplifying the work (Hultgren, 2018):

- Complex model should be cut into separate parts.
- Parts of the assembly should be designed with male and female pins.
- Tongue and groove are other options to connect separate parts.
- Adhesive works well with plastics, but the specification, of which type of adhesive is suitable for specific thermoplastic, is important to know. Also, surface treatment should be done before applying the adhesive. Acetone is a common choice for degreasing most of the plastics. However, inappropriate use of acetone can dissolve the surface of the plastic object and reduce the quality of the product.

This practical knowledge should optimize design and 3D printing process for plastic products that can be taken into consideration for designing an AI system. Machine should learn these practical features to achieve better printing results.

2.4 Stereolithography working principle

SLA undergoes to the subcategory of the VAT photopolymerization process. This technology is the oldest in the 3D printing family. The main advantages of the SLA include high quality surface and accurate finished parts (Varotsis, 2018).

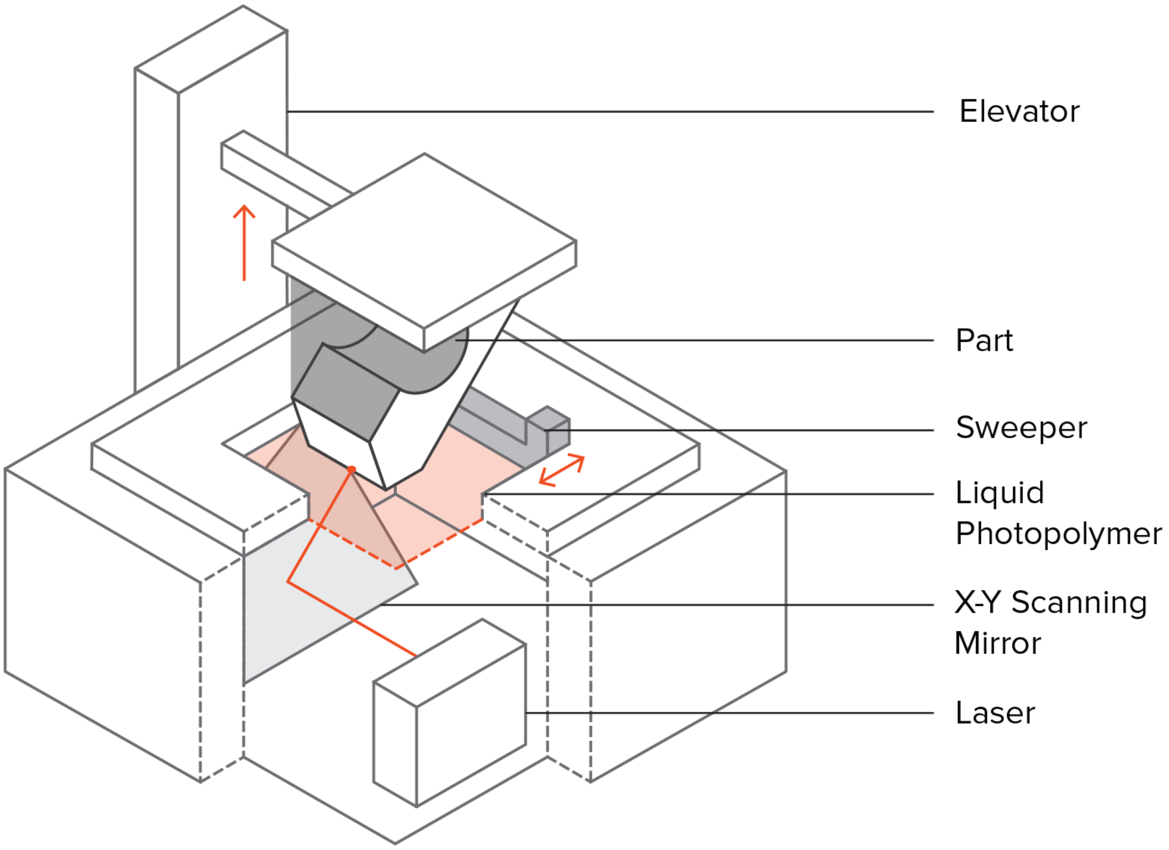

Figure 3. Schematic of an SLA 3D printer (Varotsis, 2018).

SLA 3D printer has an image projection module that shoots the ultraviolet laser on a tank filled with the photopolymer liquid. Laser beam creates a pre-programmed shape on the tank surface. Impact of the laser leads to the curing and solidifying of the pattern traced on the photopolymer. Next, build platform is lowered, then the next layer is cured joining the previous layer. This procedure is repeated before the object is finished. Printed part is cured with a solvent in a chemical bath. UV-oven is used to improve strength of the product and supports the solidification process (Varotsis, 2018).

SLA printing materials are thermoplastics and their applications are limited due to unique material properties. Formation of the thermoplastic polymers is irreversible process. These materials can stand high temperatures and remain in a solid state. Another feature of the SLA resins includes no need in post processing since printed models have high surface quality and the product can be post processed to achieve even better results, but initial state of the finalized product after printing is enough for prototypes and for component parts (Varotsis, 2018).

Engineering photopolymer materials are very adaptable and can create highly accurate models with similar characteristics to the parts produced by traditional manufacturing methods. This feature helps rapid prototyping companies not only make prototypes, but also recommend design changes for mass production methods like injection molding based on the results taken from the SLA printed model (Tofail, et al., 2018).

Jewelry is one of the youngest production fields that has started to use stereolithography to invest in the creation of accurate prototypes before the actual manufacturing. Mainly printed jewelries are used to check the accuracy and form a mold around the printed part to fill with the precious metal. This technique saves a lot of financial resources and reduces the risk of failure improving the quality of the products and customer satisfaction (Wannarumon & Bohez, 2004).

SLA 3D printers are becoming more affordable nowadays and individual consumers have started to buy these machines for reasonable prices. The main use indoors includes production of creative art products and experimental prototypes for fixing some mechanisms or just for developing individual inventions (Attaran, 2017).

2.4.1 Polymers and polymerization reaction

Polymer science consists of essential knowledge of polymer materials and their reaction to the environmental and working conditions. The word **polymer** has origins from the ancient Greek words *polys* and *meros* that mean many parts. Polymer includes a great number of molecules connected in chains. Each chain has many repeated units. Chain links are created by these units. Chain polymers are formed by bonding process of monomers and this process is called polymerization. Once polymer is formed, the links are not the same as the original monomers (Terselius, 1998).

Thermoplastics have often linear chains and branches while thermosets consist of chemically crosslinked chains (Terselius, 1998).

The process of thermosets formation is irreversible. Cross linked chains intertwine and cling to each other forming a net structure, even when the material is heated, chains are not able to move. As a result, thermoset once formed can be only burned, but not melted (Terselius, 1998).

Polymers are organic and inorganic. The first ones are formed by carbon with hydrogen, oxygen and nitrogen. Other organic polymers use instead of carbon another two elements: chlorine and fluorine. For instance, polyethylene, proteins, polyester and deoxyribonucleic acid (DNA) are organic polymers. The second type of polymers are formed by combination of boron, phosphorus, silicon with oxygen. For example, graphite, silicone, diamond and silicate are inorganic (Terselius, 1998).

Polymerization process are divided in two categories: stepwise and chainwise (Terselius, 1998).

Stepwise polymerization uses always two functional groups in the reaction. For example, ester has structure -O-CO- and groups involved in the polymerization -OH and HOOC- are cured with the detachment of a water molecule in the condensation process (Terselius, 1998):

$$CH_3 - CH_2 \dots CH_2 - COOH \quad HO - CH_2 - CH_2 \dots CH_3$$

Condensation removes the water molecule H_2O from $-COOH \quad HO-$ resulting in (Terselius, 1998):

$$\dots CH_2 - COO - CH_2 \dots$$

2.4.2 Photopolymer

Photopolymerization process has the chainwise formation which is more important for this research than stepwise polymerization. The wavelength of the laser beam promotes photopolymerization reaction which depends on the functional group of the photomonomer that should be activated (Terselius, 1998).

Photopolymer usually consists of monomers, oligomers, photoinitiators and other additives (Tehfe, et al., 2013):

- Monomer is a molecule that can react with other monomers to form a polymer.
- Oligomer consists of few monomers.
- Photoinitiator exposes under the impact of the radiation of the UV-laser creating reactive species such as cations, free radicals or anions.

Monomer and photoinitiator should have appropriate connection between each other. Normally, monomers require much more energy to activate their electrons than the functional groups in the photoinitiators. Therefore, monomers are stable and UV light does not affect the monomer. However, products which used outside for a long time receive constantly energy from the sun activating electrons and breaking the bonds reacted with the oxygen in the air. This reaction is called oxidative degradation (Terselius, 1998):

$$CH_3 - CH_2 - CH_2 - CH_2 \ldots - CH_3 \rightarrow CH_3 - CH_3 + CH_3 - CH_3$$

UV light protection additives are added to the materials to prevent oxidative degradation. Nordic countries use less UV light protection additives than southern countries because the amount of sunshine is significantly less than in the warm countries. Electrons under the impact of UV light get additional energy becoming more active for period of time needed for the photopolymerization reaction. When the reaction is finished then electrons drop back to the normal energetic level (Terselius, 1998).

Material changes its properties when exposed to light. Photopolymer liquid is cured in regions only where the UV laser shoots. Curing process leads to the bonding of chains in cross-linking reaction. Induced polymerization by UV light is followed with solidifying and hardening of the material (Varotsis, 2018).

VAT polymerization process works with the following materials according to (Bourell, et al., 2017):

- Acrylics
- Acrylates
- Epoxies

Viscosity of the feedstock is important for this process. Addition of particles should not prevent the reflow in the working region (Bourell, et al., 2017).

One of the first photopolymer materials, which has been used for the photopolymerization, consisted just of acrylate monomers and photoinitiators. Also, vinyl ether monomers were used in resins, but significant warpage of the material was caused by shrinkage from 5 to 20 %. Solution for material problem came in 1990's with the development of the epoxies. This material has excluded previous issues, but the formulation process of the resins became more complicated (Bourell, et al., 2017).

Epoxy is a cationically polymerized polymer. Chemical bonds are formed with the opening of epoxy monomer rings. Volume change is not significant in this reaction, because the amount and type of chemical bonds is the same before and after ring-opening. Considering this fact, epoxies perform better than acrylates due to the shrinkage and warping resistance (Bourell, et al., 2017).

2.4.3 Laser

Lasers are playing significant role in the medical field as industrial working tools and as essential equipment for the computer science. One of the most powerful examples is the 20-kW fiber laser made by IPG Photonics (Oxford, MA). This laser fractures and softens the rock allowing the drill to quickly make a hole with the decrease of required energy in 90% (Hecht, 2012).

Laser cutting methods are proved by their accuracy and reliability as well as in welding techniques. Many other industries use laser technologies according to their needs and the prediction of the laser market grow is 16 billion dollars in 2020. Despite of the application variability and uncertainty of the main working area, additive manufacturing is the one of the most prospective field which uses lasers (Pinkerton, 2016).

Lasers are used in directed energy deposition to collect the energy in a focused beam and fuse the material by melting. Also, powder bed fusion technique uses laser to fuse patterns on the surface with the thermal energy (Tofail, et al., 2018). However, the research is focused on the category where the laser technologies are used in the VAT photopolymerization. The photopolymerization reaction starts in specific regions affected by the UV-laser beam in the SLA 3D printing process (Varotsis, 2018).

Printers with lasers are usually covered with protective shield from the oxidation and harmful risks to the operator. This feature is taken into the consideration by the 3D printing companies to develop user-friendly machines which one day will be used by their customers not only at the industrial manufacturing areas, but also at homes of the usual consumers (Lipson & Kurman, 2013).

Power and wavelength are the main elements of the laser. Variation of these parameters can be very different starting from 1 W to 6 kW and from the UV 354.7 nm to the IR 10.6 µm (Pinkerton, 2016). Laser selection depends on the polymer absorption spectrum for SLA.

These numbers can be frightening at the first sight, but if the SLA 3D printing is compared to the other traditional manufacturing methods then the conclusion is quite clear that AM technologies are better in production of small batches and not suitable for mass manufacturing. However, 3D printing has a promising future with technological development and possible replacement of old manufacturing techniques (Rogers, 2015).

Also, SLA technology does not have indirect costs while injection molding requires preparation, planning, production, delivery of the mold, etc. AM has different materials and this technology does not require additional transportation. Digitalization of the AM process is one of the main advantages which makes customization process quite simple without the need of any tools. All operations regarding 3D printing process can be done on the remote, potentially even in space. These factors save time and make the SLA one of the best techniques for the rapid production with the quick response to the customer inquiry (Rogers, 2015).

2.4.4 Photopolymerization process

According to (Penczek & Moad, 2008), there are four main steps in the curing process of the photopolymer:

1. Initiation
2. Free radical formation
3. Propagation
4. Termination

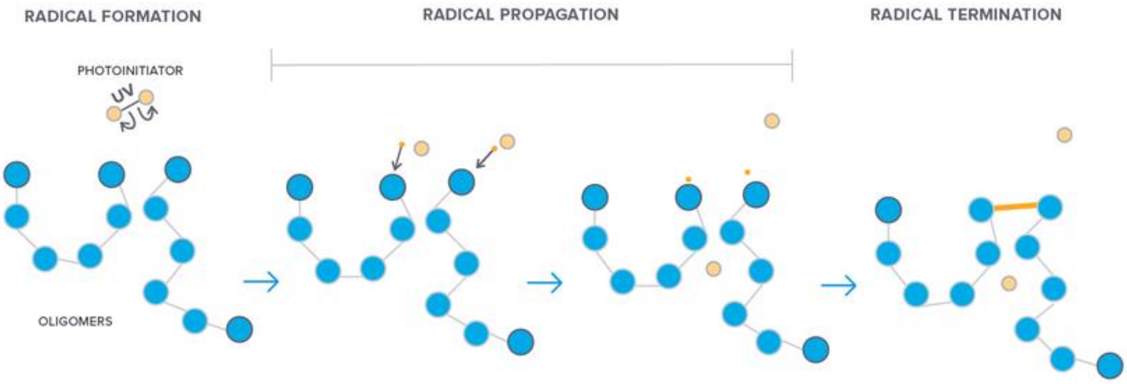

Figure 4. Polymerization (MIT, 2018).

Initiation (Terselius, 1998):

$$CH_3 - CH_3 \rightarrow CH_3 \cdot \cdot CH_3$$

SLA 3D printing process uses free radical formation. Radicals are formed and separated from each other under the exposure of the UV light. Radical polymerization is related to the acrylates (Terselius, 1998):

$$CH_3 \cdot \cdot CH_3 \rightarrow CH_3 \cdot (radical\ 1) \quad \cdot CH_3 (radical\ 2)$$

Also, anion and cation are formed with the different bonding mechanisms. If the monomer is strong enough to keep electrons then anion is formed, otherwise if the initiator takes the electrons then the cation is created (Terselius, 1998):

$$CH_3 \cdot \cdot CH_3 \rightarrow CH_3 \colon (anion) \ \ CH_3 (cation)$$

Anion (Terselius, 1998):

$$CH_3{}^-$$

Cation (Terselius, 1998):

$$CH_3{}^+$$

Propagation is the next step of the reaction meaning the rapid grow of the polymer chain (Penczek & Moad, 2008):

$$polymer\ (M)_n + monomer\ (M) \rightarrow (M)_{n+1}$$

Termination is the last part of the chainwise polymerization reaction. Ends of the polymer chains face each other creating a bond (Terselius, 1998).

Active groups are not able anymore to create new bonds. The polymer chain grow process is terminated (Terselius, 1998).

2.4.5 Practical knowledge

There is some important knowledge that have been collected during the studies and work with the SLA technology. Formlabs PreForm slicer program has an important feature: user can manually create and remove generated supports ("PreForm Prepares Your", 2018). This affects the risk of the printing failure. Additional supports should be added for overhanging parts in excess of 45° (Hultgren, 2018). After printing is finished the platform should be removed by holding on the sides without touching the platform surface. The part should be designed with the small hole in the basement to avoid creating vacuum. Otherwise, removing the printed model is extremely hard without breaking (Hultgren, 2018).

Post processing of the printed part requires curing with solvent in chemical baths. The first and the second bath should be used for a few minutes each as a common rule. Bath requires a flow inside the liquid solvent ("Learn More About Basic", 2018). According to independent observation and experience, the process can be optimized by the simple trick: the small magnet is placed in the bath under the platform where the object is located. Next, magnetic field is created by placing the magnetic stirrer under the bath creating rotational magnetic field. The magnet rotates in the bath without touching the printed part creating the flow inside the solvent. Otherwise, the part should be agitated manually ("Learn More About Basic", 2018).

2.5 Artificial intelligence science

The impact of AI technologies is becoming more widespread. AI changes the everyday things and ways of organizing life, labor market, relationship of sellers and buyers, different ways of consuming the information and services. However, the fate of the future world, economy and politics, issues of war and peace do not directly depend on the development of AI technologies (Karelov, 2018).

There are some good visionaries among the top information technology (IT) giants. Unfortunately, the trouble is that for various reasons, especially commercial, AI developers prefer to keep quiet about the most important, providing an opportunity to broadcast about the future of AI to the marketing and public relations representatives of their companies. However, occasionally information breaks through the engineers. This is the most honest and important information about the future technologies and perspectives (Karelov, 2018).

For instance, DeepMind co-founder Demis H. has outlined his vision for the future of AI at an economic innovation summit in London (Heath, 2018).

Three main points were formulated (Heath, 2018):

1. AI can save humanity from itself, and first of all, in the field of geopolitics.
2. By compensating for the worst consequences of human greed and selfishness, AI development will revolutionize the whole science, generating a series of discoveries of the Nobel level.
3. Deep learning is not enough to solve the problem of general AI. Following today's mainstream AI research and development, this problem cannot be solved. Interdisciplinary, brain-like approaches and fundamentally different concepts of AI are needed: not the current Artificial Intelligence, but the True Intelligence.

Artificial intelligence is a new field of science and there is no standard definition. However, the best way is to explain subject with supporting examples.

Vehicles with implemented AI system are able to find and organize the most optimal destination way. Computer vision is applied to scan the environmental situation on the road. AI system makes intelligent decisions to interact with surrounding objects in appropriate manner. System should learn a lot to avoid accidents. Machines will drive themselves in the future while humans should supervise them if needed (Coppola, 2018).

Personalization of the online content is developing now due to the AI recommendation system which works with social networks, movies, advertisements and videos. Potentially, AI system should filter content not related to the specific customers’ interest and fake news. AI system will be able to perform any task without human supervision. Also, artificial intelligence can learn and adapt (Naik, 2017).

The correct understanding of related fields to AI is an important part of modern science. Artificial intelligence is a system that can work with specific problems and make intelligent decisions (Chace, 2018).

2.5.1 Computer science

Computer science is the general discipline which includes realization of the processes, theory and design of the computers. This discipline develops programming languages, analysis of algorithms and protocols of transferring data. The main research works are aimed on the computational theory and artificial intelligence nowadays. The computer scientist deal with the solving of specific informational tasks using programing languages with maximum efficiency. Problems of storing information and transferring the data is also a part of computer scientist work. Interaction between digital information and human brain is the main field of the data representation in computer science (Denning, 2005).

2.5.2 Machine learning

This is a subfield of AI which studies techniques for building algorithms capable of learning. In other words, machine learning (ML) is a tool that AI uses to accomplish specific tasks that is based on the precedent or inductive learning. This type of learning includes identification of private empirical data from general patterns. ML gathers the information, analyzes and presents independent solution. Accumulation of information and working experience gives the machine an opportunity for improvement and finding new solutions (Bishop, 2006).

2.5.3 Deep learning

Deep learning (DL) is the part of the ML. Constantly increasing data with learning algorithms are transmitted to large artificial neural networks, increasing the efficiency of processes such as thinking and learning. The learning process is deep, because neural network covers an increasing number of levels over time, and the deeper the network penetrates, the higher performance rate becomes. Despite the fact that most of the deep learning is processed under the control of human, the goal of scientists is to create neural networks capable of forming and learning independently. This subfield allows researchers to focus on the information, about specific subject, produce new data and correct earlier information with the powerful modern computers (Brownlee, 2016).

2.5.4 Data science

Data science includes ML and statistics, some aspects of computer science, keeping the information, online implementations and calculating algorithms, and a bit of AI. This professional field includes effective and reliable search for patterns in data, extracting information in the generalized form suitable for processing by interested users such as human, software system or control device. This process is essential for making informed and reliable decisions (Paskin, 2018).

2.5.5 Robotics

Robotics is the science about designing and programming robots to operate in the real-world conditions. This discipline requires implementation of almost every part of modern technologies such as: speech recognition, computer vision, natural language processing, cognitive modeling and affective computing to interact and work with humans. Robotics includes such disciplines as electronics, mechanics, programming. This field of science has wide application in the building, industrial, domestic, aviation, military, space, etc. ML is essential for robotics to solve most of their problems. The development of the robot control methods is based on the technical cybernetics and the theory of automatic control systems (Perez, et al., 2018).

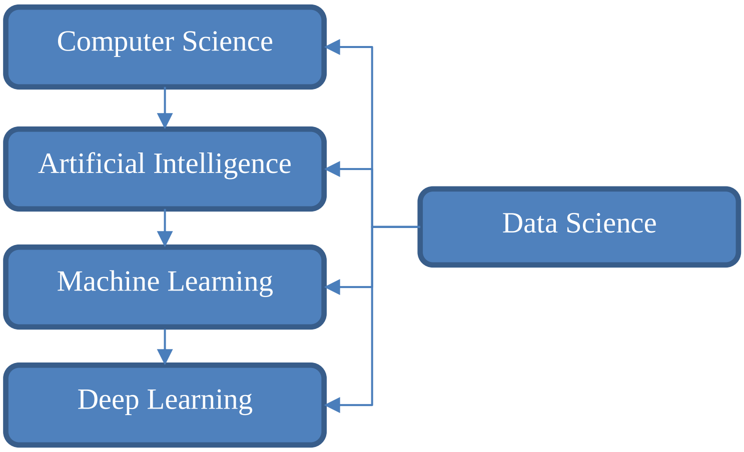

Figure 5. Artificial intelligence in science.

2.5.6 Science fiction and the real state of AI

There should be a clear separation between science fiction and the real state of AI that the society has now. Real AI which is known as Narrow AI or Weak AI is a system that handles few tasks or even one. The machine always learns and makes progress with intelligent behavior despite being usual computer. General AI or Strong AI does not exist yet, but probably AI would be a real and self-conscious system which is able to handle any intellectual task (FCAI, et al., 2018).

On the one hand, general AI would be able to perform any task in the real world when usual computers are limited in solving every possible problem. On the other hand, narrow AI with the help of ML system is constantly improving itself coming up with absolutely new solutions that the system has not been programmed to do from the beginning. AI and ML are parts of computer science, both systems can be implemented in a usual computer which can change the average computer from being "mere" (FCAI, et al., 2018).

AI system does not have a realization of itself, but machine responds to the human as a self-conscious mind. Robot can interact with the environment as a human, following typical behavior patterns and programmed ethic rules. This feature creates an illusion of a real creature despite the fact that machine just imitates our behavior (FCAI, et al., 2018).

Adaptation and studying of data with the environment are done due to the ML. Autonomy of these systems has the place in our world, because AI system makes independent decision based on the offered solutions by ML system. However, modern AI systems need supervision from the human to control and correct the process if needed (FCAI, et al., 2018).

AI is an intelligent system that can handle programmed tasks coming up with new solutions based on its own learning experience and collected data. Future potential of AI is an ability to set unprogrammed new tasks, learn and solve them according to the rules and human ethics. AI science requires research and development to become fully independent system without human supervision (FCAI, et al., 2018).

2.5.7 Current AI applications and problems

The main problem of AI in autonomous vehicles is to predict behavior or even the way of thinking of human drivers and pedestrians. However, Toyota AI Ventures and Hyundai Motor announced the new project where both companies are going to work on the problem of introducing of human intuition into autonomous cars. Perspective Automata received investments from both of these companies working on the technology of human behavior prediction system (Coppola, 2018).

The company started from the analysis of the human body language to understand where and how the pedestrian will suddenly move in the case of the possible danger on the road from the vehicle or just in the situation if the person is in the hurry. Decision of AI system is based on the intensions of what the individual is going to do and awareness of what the pedestrian knows about the approaching vehicle. AI models not the movement of the object, but the system analyzes the intentions (Coppola, 2018).

This is a complex problem to work on, but then the future of the automated independent cars is going to be prospective. These vehicles will be fast, accurate and safer than the manually driven cars. However, there will be another problem after building an AI system which predicts intensions of pedestrians. This feature will include identifying and analysis of the person who drives another vehicle (Coppola, 2018).

Emotions remained beyond the computational approach for a long time. At the same time, the one common fact was considered: if the algorithms of AI become sufficiently advanced, then there will be a possibility to fasten AI technologies and build on top of these achievements the emotion control subsystem (Karelov, 2018).

Such an idea not only dominates today in almost all AI technologies, but also this trend has become a part of the mass consciousness, about which a lot of books, films and TV series tell every day (Pessoa, 2018).

However, these ideas are impossible now in the real world. In contrast to the modern ideas about AI, natural intelligence is different. Emotions and cognitions are part of one whole thing, and their modeling requires a single architectural implementation. In such a way the human revolution has been created over the millions of years. Artificial intelligence evolution still needs to be developed (Karelov, 2018).

The processes of perception and knowledge of an individual human are inseparable from emotions. All attempts to postpone emotions for later time, in order to build them on top of the algorithms, which are developed in the framework of the computational approach, are not successful (Karelov, 2018).

These attempts can create the regular smart machines, although technologies can beat a person in computer games and do a lot of work for people, but machines do not possess emotional or cognitive intelligence. The modern world is not a game, but an interesting topic about the enormous complexity of the transition from an AI-playing to an AI-working can be reviewed (Karelov, 2018).

The most impressive achievements of AI are in the field of games nowadays. Absolutely overwhelming superiority of artificial intelligence over human intelligence has already been achieved exactly in this field. This is not only about the incredibly high level of the game played by the AI. Also, this topic is about the machine logic and aggressiveness of the AI way of playing the game (Karelov, 2018).

AI is clever in the field of games. However, this field of science with innovations does not only show being super-intelligent outside of the games, but artificial intelligence is not even able to reach the level of ordinary people.

According to (Chace, 2018), a key factor of the AI achievements in games from chess and poker to cyber sport computer games consists of the learning ability. The program with implemented AI on a specific machine learns the game, not taking over the skill from a person, but playing alone or with the same modified copy. This allows artificial intelligence to overcome two fundamental limitations (Karelov, 2018):

1. Limitation of the lack of data. Individual person needs to read and memorize tens or few thousand chess games from previous tournaments, while self-study of AI requires millions and millions of games that the program can easily analyze and remember.
2. Limit of the time speed. The game world is generated by the computer, and the time flows with the speed of calculations, not like in reality. The programmed AI bot can play alone having as much data as possible. The most important thing is that all this training can occur so quickly that the human cannot even notify and realize.

The world is completely different from the games as follows (Karelov, 2018):

- The complexity of describing the goal or the objective function is the main point. The goal of any game is described simply. On the other hand, this is extremely difficult to describe exact target for a self-driving car in the real life.
- The game is clearly determined, while the world is unpredictable. First of all, prediction of the actions in the real world are not stable. AI system cannot imagine what is the definition of the title in chess if probability is necessary for consideration of stealing a figure from the board by the opponent. Players owning perfect information know everything about the game process. Real world does not have perfect rules and information. The same situation would be if AI system chooses

a move, periodically without knowing the location of the pieces on some part of the chess cells area.

AI system should have a realistic model of the world in which the program makes a decision (Karelov, 2018):

- The primitive model for board games is required.
- More advanced model required for arcade games.
- Difficult model is created for cyber sport games.
- The real-world modeling is so complex that implementation of all modern technologies in robotics requires replacement of body and sense organs with sensors, automated parts, machine learning software systems, human speech recognition, etc.

2.5.8 AI in modern society and possible consequences

Massive implementation of AI has a lot of discussions about dangerous consequences which are not unreasonable, but very exaggerated. Weaning of jobs and the intervention in the course of essential events by AI are real, but the situation is not so awful. Adaptation to technological progress in society already has centuries of experience. Humanity will cope with challenges from AI (Karelov, 2018).

The weak point of the high complicated system of the future society is not the vulnerability to AI threats and the problem does not include the public reaction to the risk of these threats growing. The main problem consists of the following points (Karelov, 2018):

Possible mass replacement of working citizens with AI-automated systems can lead to the panic that will rise among the people in the potential areas such as infrastructure. Escalating panic for the fear of lack of working places, without consideration of different alternatives the AI can present to people, is the possible reason for the following situation (Karelov, 2018).

Society gives an opportunity to the politicians to make new laws and limitations regarding development of AI. Already now there are some famous and influential persons trying to use the situation and ban the development of AI in different areas to keep control in personal interests calling AI as the main enemy of humanity, while machines do not have emotions and desires related to the personal gain. (Karelov, 2018).

Technological industry is mainly aimed on the reaching the highest amount of profit. However, companies can change the direction of the AI technologies development (Karelov, 2018).

As a result of the previously presented problems, the world can develop to the following situation (Karelov, 2018):

- Most of the people will live at the minimum survival level financed by the achievements of the robotic labor force.
- Isolated society of special people, who control robots, will rule the world and achieve significant wealth.

These possible developments of the future society are unstable and ambiguous (Marr, 2018).

According to (Ian & Nathan, 2018), there are only 2 million industrial robotic machines existing in the world, which is very small number related to the amount of people employed in the modern society. The growth of robotization is 14% per year (Ian & Nathan, 2018).

The leading countries in robotization have the largest number of citizens. For instance, there are only 168 robots per 10k in the US, in China, less - 68 (Ian & Nathan, 2018).

There are only 22 thousand specialists in the world with PhD training in AI (Ian & Nathan, 2018).

Most of the AI workers are in the largest corporations: 1,400 in Google, 1,000 in Microsoft, 900 in IBM, 450 in Baidu, 400 in Tencent and 300 in Facebook (Ian & Nathan, 2018).

These facts exclude any problem for now and in the nearest future of the mass replacement of human resources by the automated systems and robotics (Ian & Nathan, 2018).

3 METHOD

3.1 The main reasons of the failure during the SLA printing process

The first step of the practical part of the research is to identify specific failure reasons in the SLA 3D printing process:

- Photopolymer material failure.
- UV-laser wavelength change.
- Curing reaction violation. Molecular chains are linked by the impact of the light creating polymers.

Possible SLA failure happens in the surface layer. Solution of this problem could be found by focusing on the curing moment, but first, UV-laser beam and photopolymer material should be studied, because these elements are directly involved in the curing reaction.

3.1.1 Solution

AI system with the computer vision system should be developed for real-time 3D printing control to scan the layers, collect the information, analyze and fix the failure without interruption of the SLA printing process.

3.2 The working concept of the AI system for SLA printing

Sensor system with computer vision should be created and used to find defects scanning each printing layer. AI system could collect and analyze printing data, then immediately correct the failure in the problematic layer or compensate the damage in the next few layers. The best way would be to predict the failure and make quick changes with AI by following actions during the printing process (Bharadwaj, 2018):

- Adjust the laser settings to control the wavelength.
- Modify structure or pattern.

- Adjust movement of the build platform to change the thickness of the layers.
- Change the composition of the photopolymer by adding other substances such as photopolymer initiators. This solution requires creation of the system that could immediately mix photopolymer in the tank.

The failure should be fixed on the earliest stage. Machine should identify divergence from the design and solve the problem as soon as the problem starts to appear. Therefore, the following properties should be developed:

- Sensitivity of the sensor computer vision system.
- Reaction of the machine defining the error.

3D printing is an additive manufacturing technology. Machine adds the material layer by layer. The other way to fix production failure is to create a 3D printer which could remove material from the failed region. Next, AI should analyze the problem and find another way to build the product without changing final product properties. Properties of the product must correspond to the design, so that the manufacturer can be confident about functionality and quality of the product.

However, product cost would significantly rise after implementing computer vision and AI system for manufacturing process. This technology could be developed for a medical industry since every product must replace a part of a human body which is almost priceless. Quality of the product is the most important attribute on the market of medical implants. Each product can be sold at a very high price that perfectly solves the problem of the production cost.

The first prototype could be developed and installed on the small SLA printer to reduce investment of the financial resources required for the research. Next, experiments of the printing the same product should be conducted with and without AI computer vision system. Information should be analyzed and compared to find the increase in quality of the product. Another set of experiments should be conducted for the product designed with the failure. System would collect the information for each experiment, analyze and fix the problem. AI should constantly improve itself. If the results are constantly improving, then the system works successfully.

3.3 Optimization of the design process with AI

AI in additive manufacturing has been already implemented to develop generative design process. Next, AI system should be used to control the printing process. In the first step, design process needs appropriate optimization. Several companies are working on the development of the generative design system and optimization topology method, however there are only few studies about real-time 3D printing control.

Generative design system allows user to choose between different solutions for the design of the product based on starting parameters such as strength and weight with the analysis of materials, manufacturing techniques and evaluating costs. Designs are optimized by adding and removing the material where necessary. Light and strong parts with complex shapes are usually produced with AM combined with generative design (Baklitskaya, 2016).

For instance, Airbus company reduces amount of material in airplane parts, without losing reliability and quality, and fuel cost is lowered with implementation of the generative designed parts that leads to the reduction of carbon dioxide emissions ("Autodesk And Airbus", 2016). This is a good example of how the optimization saves not only company expenses, but also improves the quality of life and protection of the environment.

Printing process is evaluated before, during manufacturing process and after that. Defect detection and correction during the 3D printing process without interruption is the main interest of the thesis. This is a unique research since there are no studies done for real-time printing control of the SLA 3D printing technology.

3.4 Implementation of machine learning in the SLA 3D printing

Product failure during the printing process is a serious problem for manufacturing industries which leads to material and time waste, reduces productivity and damages the economical part of the companies. Reduction of the risks associated with production failures leads to raising production technologies to a completely new level. The printing process has different problems that can be analyzed and solved much faster and better by the computer system rather than by an experienced individual person. This idea requires a lot of stored digital information of the printing processes and failed parts. Immediately, the question arises: How to collect all the necessary information and save the data?

The solution can be found in the invention of computer vision system equipped with the scanning cameras and computed tomography to collect printing information.

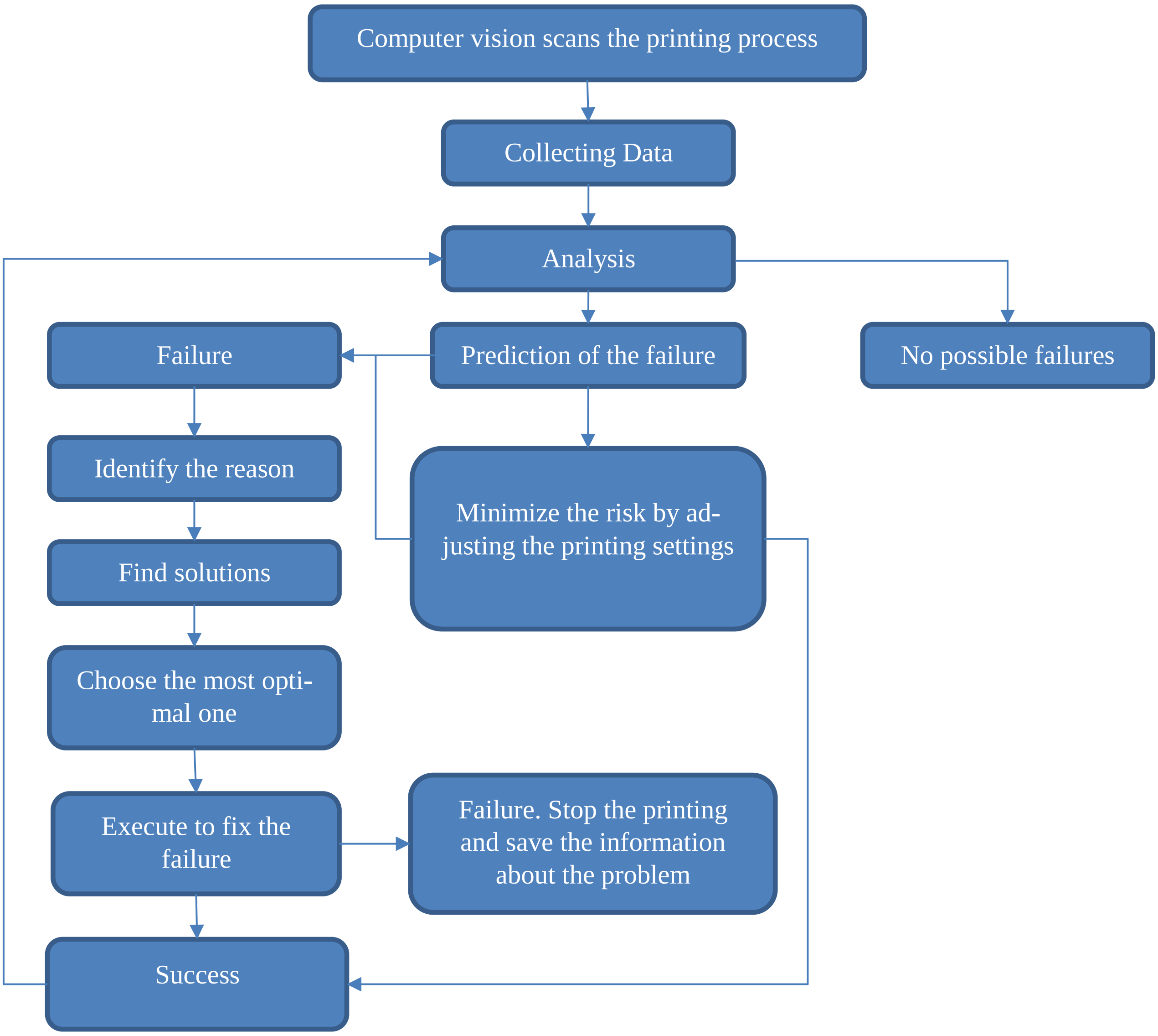

Figure 6. Self-learning machine concept with the scanning system algorithm.

If the problem occurs during the printing process, then the failure should be detected by the implemented additional sensors. The possible equipment for creation of such a technology includes:

- SLA 3D printer

Affordable SLA 3D printer such as Formlabs desktop printer. This SLA 3D printer Form 2 has specific properties that are suitable for the project. Any other printer can be used, but Formlabs printer has reasonable price and high-quality printing. Finding an alternative is not an easy task, if only other kind of printer is available for use. This consideration is based on the reason for saving the funds for the project.

- Sensors

Nowadays, sensors are produced with 3D printing technologies. Therefore, the body of a sensor can be produced with the same Formlabs printer, but technology requires its functional electronic part which can be ordered from the industrial electronic companies. However, there are some specific properties required for appropriate work of the sensors in the environmental conditions of SLA 3D printing process including UV light protection screen, chemical resistance to the photopolymerization reaction and to the photopolymer material, protection from interferences inside the 3D printer and from the movements outside of the printing space. All these precautions are necessary for the correct operation of the sensors and for the information analysis.

- Scanning cameras

High resolution scanning cameras are a good option to control and gather the data about printing process observing the surface of the printing model. This technology is often used in automation to control production process.

- Computed tomography (CT) scanning system

Computed tomography scanning technology should be used to inspect failure risks inside the structure of the object. This scanning is commonly used in medicine to get the multi-layer examination and information about human internal organs using X-rays (McKenzie & Goergen, 2017). However, the same principle can be used to study each printed layer and internal structure to find information and use this knowledge to predict possible failures.

- Machine learning deep algorithm

Algorithm should be based on approaching the task of achievement the successful strategy for printing digital model. Every element of the algorithm should be formulated clearly, so that the program can decide only between two options for each step either positive or negative. The concept of the algorithm includes collection of the printed data and analyzing process with creation of possible solutions for occurring problems.

- Software

The software for the machine learning system should be created with the machine coding which is a very primitive, but complex at the same time. Most of the machine coding instructions are written with the high-level coding languages translated to the original form with the support of compilers. These technologies work with the computer code created in the specific programming language to translate the information to another coding language. High-level language coding was created to simplify and increase the speed of the coding process for programmers. Machine code is the native code that machine can read and execute to complete the specific task (Rouse, 2018).

Machine learning programming languages are different and may be used for various tasks. Some languages are better for the particular situation while others are not. Therefore, there should be possibility to learn and use following languages ("Programming Languages For", 2016):

- Python is the most common language for beginners in the field of machine learning. This language is unique, because Python is implemented for various tasks. Most of the algorithms are based on the linear algebra and common methods of machine learning.
- R language is used for creation of statistical instructions. This programing languages has specific packages that allow user to simply build strong algorithms visualizing the execution process. The main application fields are research and industrial development projects.

- C language was the first programing language which became the basement for creation of all other languages. This option is the most difficult one and can be used only by professionals with the strong knowledge in programming and building algorithms. However, if the person can use C language then there are no more limitations for creation of advanced instructions for the machine.
- There are more specific functional languages that can be used for experienced programmers such as Haskell or Erlang. The first one is well known for serious typing functionality and ability to interact with various languages. Erlang is a functional programming language typing, the main feature of which is programming at the level of individual separate processes with an ability of communication by sending messages that do not coincide with anything in time.

The required human resources:

- 3D printing engineer should have the knowledge of additive manufacturing processes, especially about SLA printing features, with product failure experience in the same field. The person should be able to study the failures and give the analyzed information presented in an understandable way with the possible corrections and solutions to the machine learning specialist.
- Sensors technician is responsible for finding appropriate and accurate ways of installing the sensors for detection of possible failures inside of the SLA printing space.
- Automation engineer with the focus on the computed tomography scanning technologies. The main responsibility should be analyzing the information given from CT scan and presenting the results to the software and machine learning developers.
- Machine learning specialist should create an algorithm with the set of instructions which lead to the analysis and improvement of the 3D printing process based on the information presented by the 3D printing engineer.
- Data scientist with the knowledge of machine coding receives an algorithm from the machine learning specialist. Next, the main responsibility is to create a program which executes each step of the algorithm in a correct way.

3.5 Compensation of the failure with the control system of the layer thickness

The second case is the prediction of the possible failure and compensation of the problem in the layers before the failure. If the problem is predicted, then certain actions need to be taken to minimize the risk of the failure. The solution is in the reduction of the layer thickness. Printing layers before the failure can be changed in the internal structure, amount of the infill material and the settings of the UV laser can be adjusted for these layers to make photopolymer harder or softer. Movement control of the build plate is the solution for this problem.

Printing of the part should be done with the layer thickness at least as twice as the minimum printing layer. For example, the possible problem has been detected by the sensors and the system predicts the failure after next few layers. The amount of the layers should be immediately increased with the reduction of their thickness to the minimum. The build plate moves less with each layer giving more chances for the computer system to correct the possible error.

Another case is about the situation when the failure has just happened, but the problem is not so significant, and the error can be compensated in the next few layers after the problematic one. The principle is the same: thickness of the following layers should be reduced as soon as possible allowing the computer system to make corrections with higher chances of success.

However, some consumers like dentists or jewelry professionals have high quality standards and may not accept such solution. Anyway, SLA technique has wide range of various applications where this kind of possible compensation technology can be accepted. For instance, prototypes and rapid small batches of plastic products designed for simple purposes do not have high quality standards that have to go through a long multiple certification stages. If the compensation technology is developed enough in the future, then the invention will be able to meet high quality standards and this technology will be certified for demanding high-tech areas.

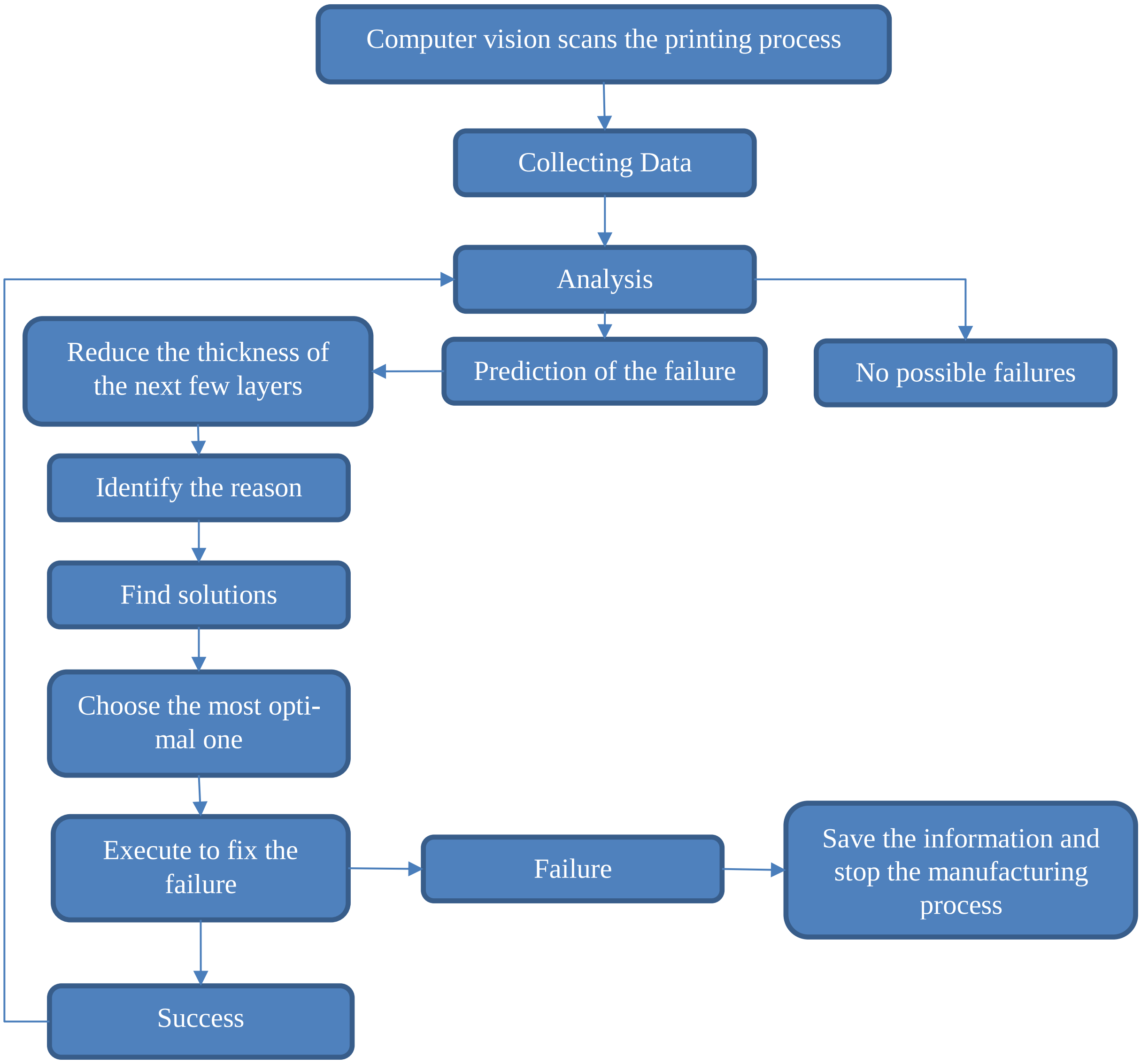

Figure 7. Layer thickness control system algorithm.

The required technologies include the previously mentioned for the machine learning system with addition of the new tasks and the following once:

- SLA 3D printer
- Sensors
- CT scanning system
- Scanning cameras
- Machine learning algorithm
- Software

- Self-adjustable build plate. The plate should be programmed to move according to the command given by the computer system.
- Computer system changes the movement of the build plate reducing the layer thickness and the system should compensate the predicted or happened failure.

The required human resources:

- 3D printing engineer
- Sensors technician
- Automation CT engineer
- Machine learning specialist should develop an algorithm for compensation of the failure reducing layer height of the layers.
- Data scientist specialized on machine coding receives tasks from machine learning specialist considering the modification of the build plate movement.
- AI research scientist develops a system which can analyze and compensate the failure with the reduction of the printing layer thickness. The target for the system is to control the movement of the build plate.

3.6 AI system real-time 3D printing control

The analyses of the printing process with possible failures is an important part of the machine learning system. However, evaluation of the printing problem and saving the information are not enough to create incredible improvement in additive manufacturing. Collection of the data requires a lot of time resources and such kind of the project is very perspective, but this idea is not going to make any significant changes in the world at the moment. Moreover, if the one great size part fails, which occupies the whole building space of the SLA 3D printer, then the model must be recycled anyway and there is no such a solution like in the previous case with the small batch. The printing must be stopped without possibility to fix the part and continue the manufacturing process.

This is a serious problem considering the fact that the cost of the 3D printed parts is relatively high compared to the traditional manufacturing methods. The solution for this case is not simple, but such an invention can be created with the help of the modern existing technologies.

Additive manufacturing is based on the adding material layer by layer. 3D printers do not remove material layers. However, the failure happens in the printed layer which can be removed, predicted or compensated in the next few layers.

In the first case, the material should be removed with the high accuracy. The tool which can be used for such an application is the focused laser beam, but not the UV laser which cures the resin during the photopolymerization process. Technology requires laser that can move in three-dimensional space. The laser should be parallel to the printed layers to cut each layer from the side. Also, the laser beam should be able to move up and down in order to cut more than the one layer. Problematic layers should be analyzed by the computer vision system and removed interrupting the printing for a short period of time, then the printing process should be continued. Despite the fact that the print can fail many times, the product will be successfully finished, and the machine will learn a lot from the problematic print at the end. The learning algorithm is enclosed, and the program will be repeated until reaching a successful result.

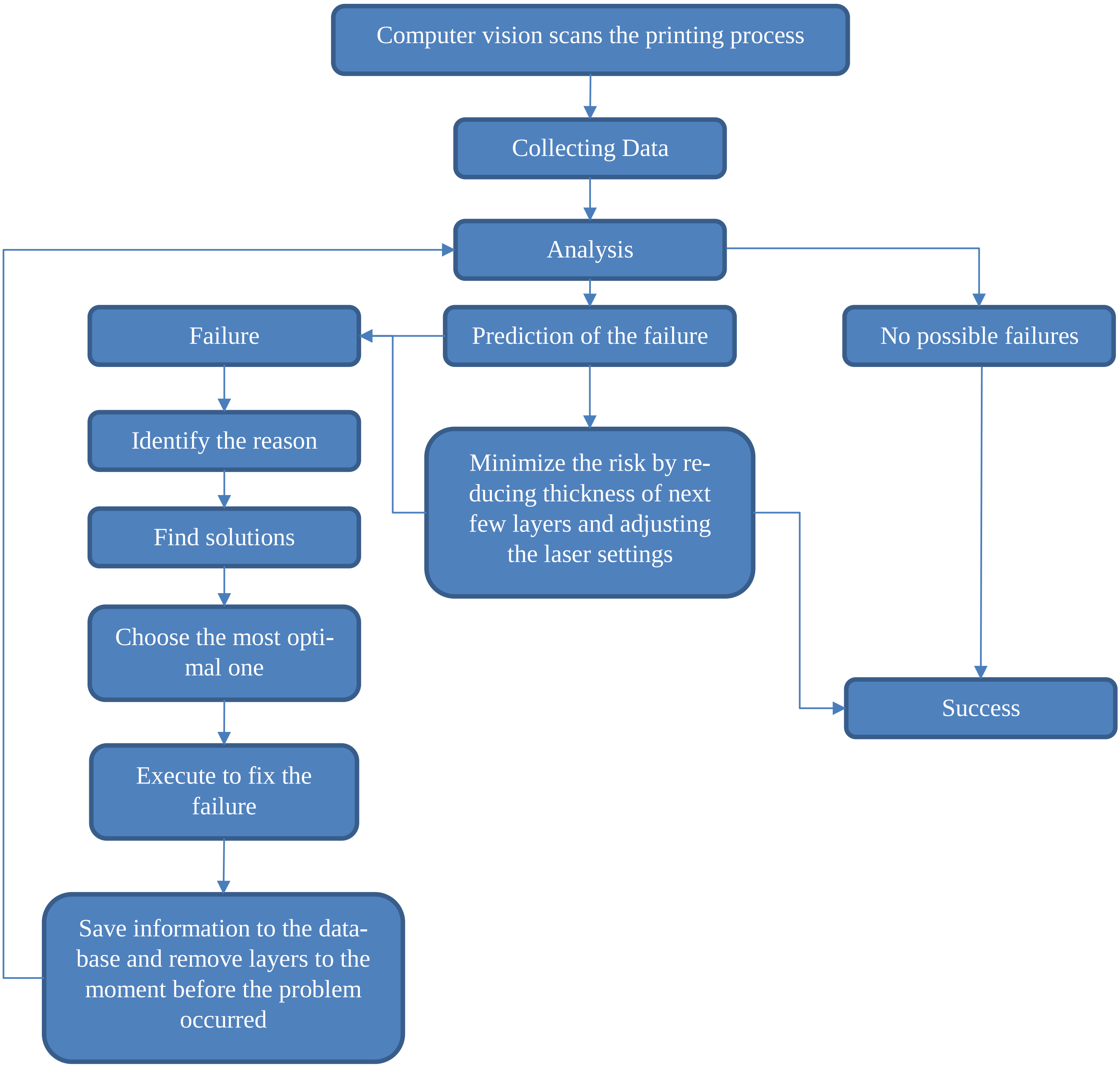

Figure 8. AI system algorithm.

In this case, the idea is not anymore only about machine learning, because the program has to make independent decisions cutting the layers that requires implementation of the self-sufficient AI system. Machine learning system just gives possible solutions and the user decides which one is the most appropriate for each case. Therefore, AI system should be created to decide and make the decision when the human is not able to react faster than the computer and analyses large set of data in just few seconds.

System should repeat the process of material removing before the machine will learn how to fix the problem. This procedure improves the fixing process with prediction analysis and decreases the probability of the failure.

The required technologies include the previously mentioned and the following once:

- SLA 3D printer
- Sensors
- CT scanning system
- Scanning cameras
- Machine learning algorithm
- Software
- Invention with an accurate laser beam which can cut with a precision of exactly one minimum printing layer. The laser should be able to move in the 3D space cutting precisely each printing layer one by one. The invention should move in vertical direction or the build platform can move instead taking the responsibility of this function.
- AI system needs to be developed for making the decisions based on the given solutions by the machine learning system. Collected information by the scanner should be analyzed and presented with possible solutions to the AI system. Program should stop the printing process for a few moments and remove the failed layers with the laser. Next, the production process should be continued starting from the last remaining layer. The amount of the failures at the beginning of launched AI system may be large, but as a human the system learns and improves the printing process. Finally, the risk of failure will be significantly reduced achieving zero waste manufacturing and high-quality products.

The required human resources:

- 3D printing engineer
- Sensors technician
- Automation CT engineer

- Laser and optics engineer is responsible for installing the laser machine inside the 3D printer and adjust laser settings according to the required invention development.
- Machine learning specialist should consider previous tasks with the new one. Additional work should be done on the implementation of the laser machine in the self-learning algorithm making the process repeatable and enclosed before achieving successful result.
- Data scientist specialized on machine coding receives additional instructions from machine learning specialist considering the invention of the laser cutting machine.
- AI research scientist analyzes the information given from the machine learning specialist and from the data scientist coding results to design AI system which makes appropriate and reasonable decisions based on the results given by the machine learning system. Scientist should easily understand programming languages and analysis plans to be able to create AI system.

3.7 Quality and quantity control

Rapid prototyping companies are using SLA printers to create not only one large prototype per print, but also this technology is used to produce small batches of products that are usually manufactured in a one printing process. However, the most common problem in this case is related to the failure in a one part of the whole batch. For instance, 10 parts are printing and one of them fails during the 3D printing process.

The SLA printer continues to print other parts and the failed part. This situation leads to the material and production time waste. The printing of the failed part can be stopped without interruption of the whole printing process continuing manufacturing of the rest parts in the same batch. This solution can be achieved with the previously discussed computer vision system. There should be a computer vision system to identify the problem, remove the problematic part from the printing system and continue printing with the rest 9 parts. Moreover, information about failed print should be stored and analyzed to prevent such a problem in the future and predict possible similar failures for the other prints.

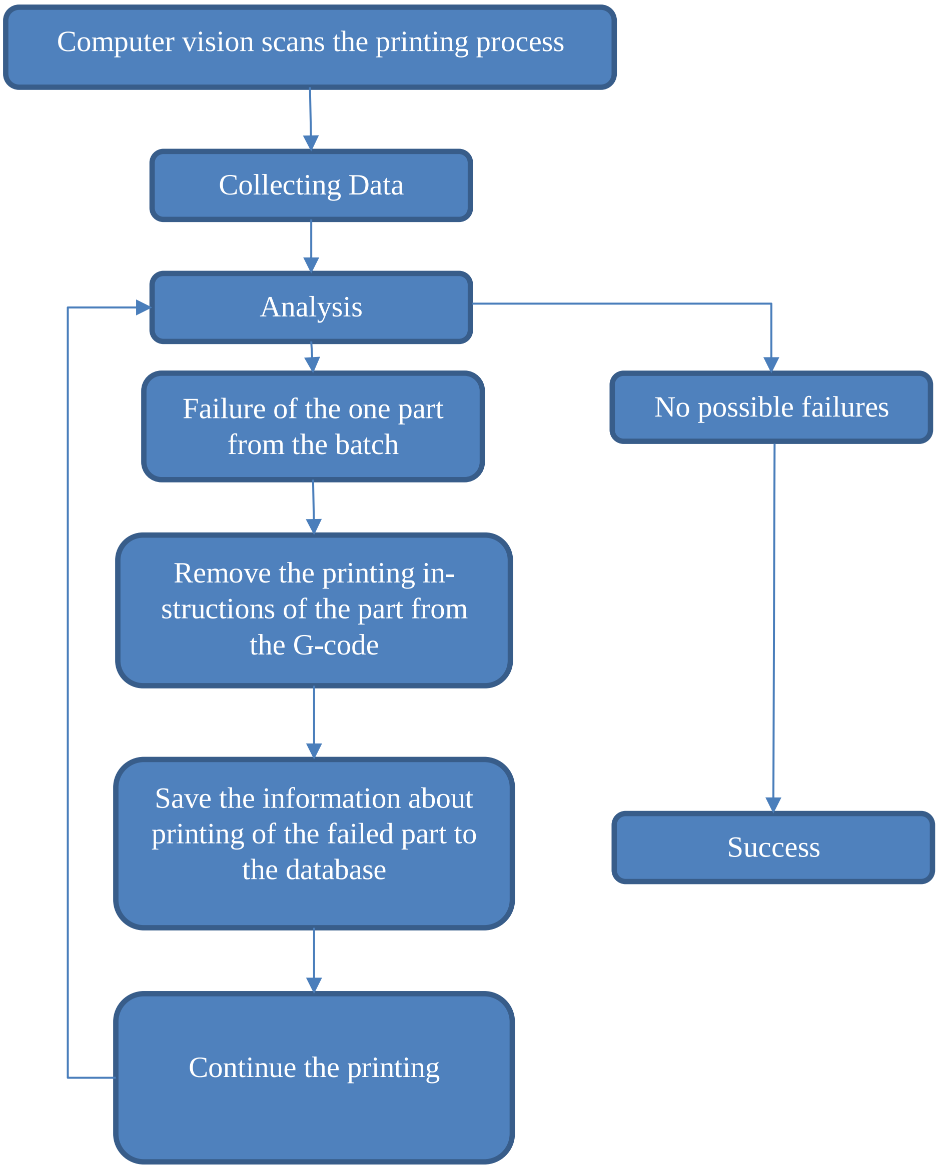

Figure 9. Quality and quantity control system algorithm.

The required innovations include previously mentioned technologies with the following once:

- SLA 3D printer
- Sensors
- CT scanner
- Scanning cameras
- Machine learning algorithm
- Software

- AI system

The required human resources:

- 3D printing engineer
- Sensors technician
- Automation CT engineer
- Machine learning specialist should develop new algorithm which cancels the failed product from the printing G-code.
- Data scientist makes the set of instructions for the 3D printer based to change the printing process if needed based on the algorithm developed by machine learning specialist.
- AI research scientist is responsible for developing of the AI system that can change the printing process discarding the failed print to save time and material, but the printing of the other parts must be continued at the same time.

The function of the excluding failed part from printing of the whole batch can be done only with usual scanning cameras which is profitable for reduction of project costs. However, the computed tomography scanner is needed still, because the analysis process requires identification of the problem in the internal structure of the failed components. CT scan is essential for machine learning system.

3.8 Sweeper adjusted wrong causing warping

Sweeper can be adjusted manually with substitution of the equal solid material blocks under the surface. The simple technique is to check if the thin stripe, which is equal to the one printing layer, nicely fits and easily moves between the blocks and the surface of the sweeper.

There should be some self-adjustable sweepers in the complex and expensive industrial 3D printing machines. However, most of the SLA 3D printers do not have self-adjustable system for resin-filled blade which swings around the bath covering top surface with the fresh material. This is an important function for the optimization of the 3D printing process since the sweeper causes warping effect if adjusted in a wrong way or if just some irregular problem occurs.

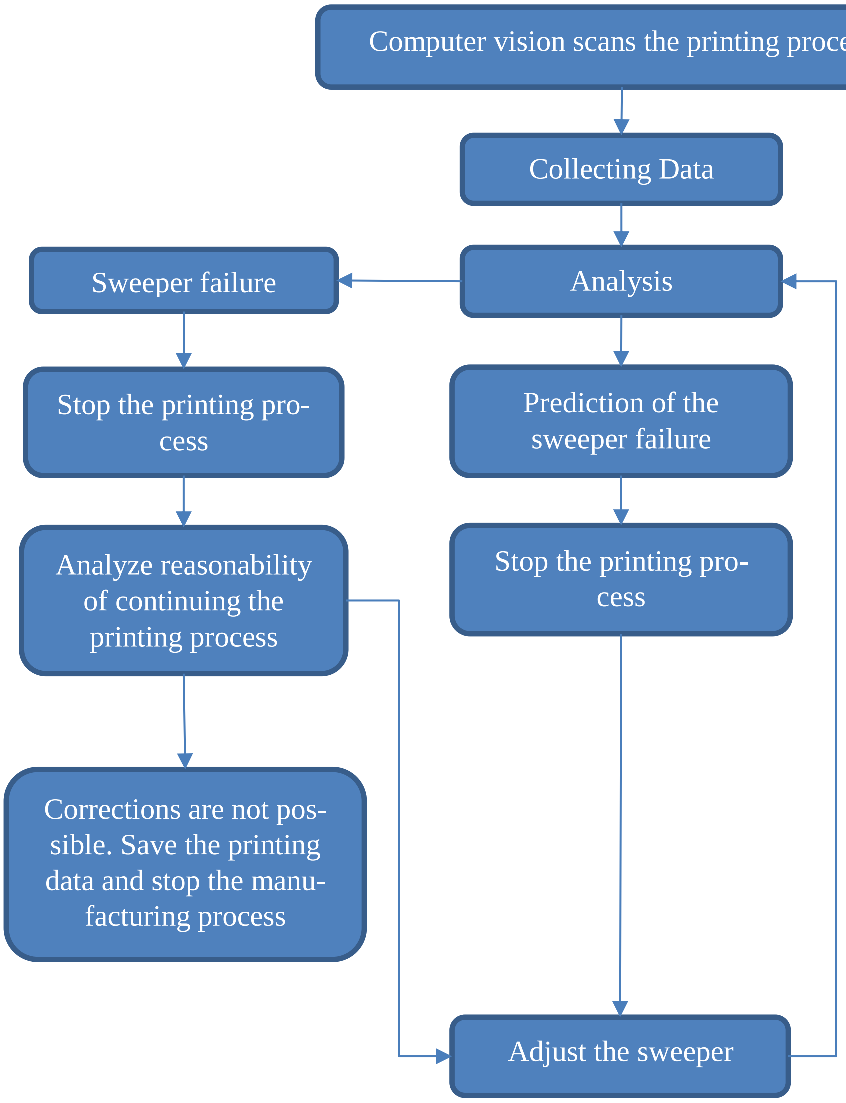

Figure 10. Sweeper adjustment system algorithm.

The system should analyze if the problem is considered as a reason to finish the printing or if the failure creates significant amount of damage, then the adjustment of the sweeper is not enough to solve the problem. Other possible AI system solutions should be implemented. Otherwise, the printing process must be stopped and repeated from the beginning, but the positive part of this case is that the information about the failed print is stored in the digital database.

The required technologies include:

- SLA 3D printer
- Sensors
- CT scanning system
- Scanning cameras
- Machine learning algorithm
- Software
- AI system should correct the movement and position of the sweeper if needed.
- Self-adjustable sweeper

The required human resources:

- 3D printing engineer
- Sensors technician
- Automation CT engineer
- Machine learning specialist should think about new algorithm for creation of the self-adjustable sweeper system.
- Data scientist should work on the instruction for the machine to adjust the sweeper when the problem occurs.
- AI research scientist receives an algorithm and coding instruction. These elements should be implemented in the AI system to adjust the sweeper before the start of the printing process.

3.9 Control over the design and supports during the whole 3D printing process

When AI system predicts the possible failure then the possible solution can be generated with additional supports for the problematic parts of the printed model. The similar technology is existing called "Generative design". However, this technology works only for the process of the design before the printing. The feature that should be developed is related to the design and support modifications during the 3D printing process.

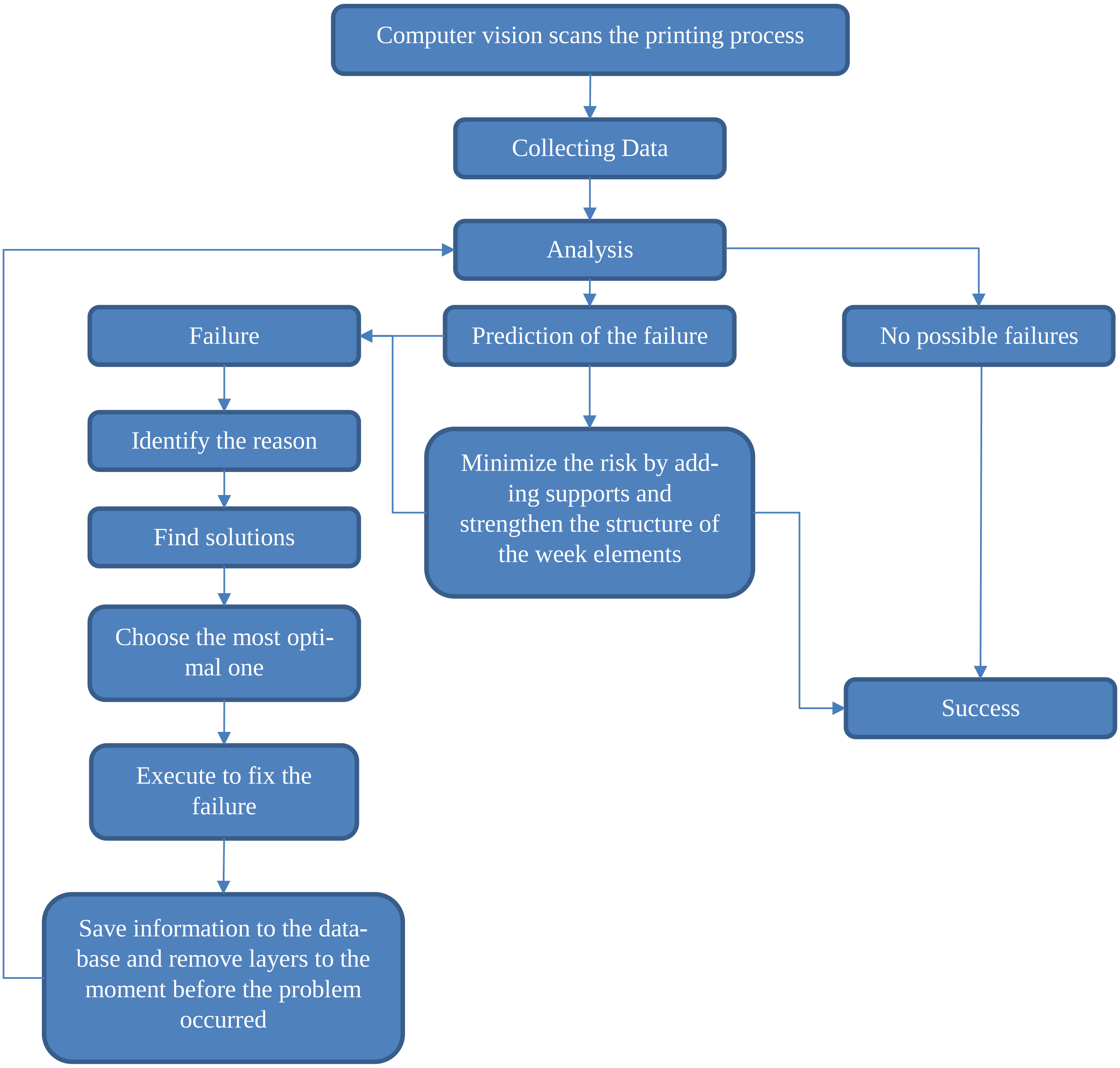

Figure 11. Design and support control system algorithm.

Problematic areas with the high risk of failure can be improved by changing the internal material structure:

The thickness of the outer wall of the printed product can be enhanced by increasing number of shells. Also, this feature helps to avoid gaps between the internal material and outer surface

Additional supports can be generated during the process of 3D printing to reduce the risk of predicted failure or to substitute supports that fell apart. Moreover, the main problem of the printing layer by layer is the overhangs. When the printing layer does not have supports or the previous printed layer, then there is a high chance of the printing just in the empty space which creates a lot of mess and problems for the next layers. Adding supports can reduce the chance of the previously mentioned problem. The solution is even better if instead of supports the AI system creates a solid structure under overhangs, but with the few support layers at the end to make the post processing much easier.

The required technologies include:

- SLA 3D printer
- Sensors
- CT scanning system
- Scanning cameras
- Laser cutting machine
- Machine learning algorithm
- Software
- AI system which generates supports and changes the design during the printing process

The required human resources:

- 3D printing engineer
- Sensors technician
- Automation CT engineer
- Laser and optics engineer
- Machine learning specialist develops a set of steps for correction of the printing and generating supports if the problem is predicted.
- Data scientist creates a code for the machine to change the design structure and generated supports
- AI research scientist analyses and implements the information in the AI system to add a new feature of the real-time control over the design and supports.

3.10 Control over the photopolymer and VAT photopolymerization reaction

One of the most common and obvious problems with the photopolymer materials is the working temperature of the resin. When the material is much colder than expected, then the print is falling apart, and the printed product does not stick well to the build plate. AI system should always check material temperature before the manufacturing and control the heat conditions during the printing process (Jennings, 2018).

Increasing number of initiators leads to decrease in the length of polymer chains, also increasing the amount of polymer chains. Also, adding photopolymer initiators reduces laser brightening time, but the lifetime of the resin is shortened since the material becomes weaker to the light exposure. Good quality material should have quite the same length of polymer chains and less branches. Therefore, adding a lot of photoinitiators to the photopolymer materials is not advised (Terselius, 1998).

However, acrylates and epoxies are mixed in the same photopolymer materials nowadays. Acrylates react quicker than epoxies improving speed of the reaction and reducing the amount of energy required for the reaction of the epoxy. Polymer networks are formed by cationic polymerization in epoxides what leads to the strengthening of the cured material. Interpenetrating polymer network (IPN) is created during the chemical reaction. Two polymers in a network form, created by two concurrent reactions, produce a special class of polymer blends IPNs (Bourell, et al., 2017).

Inhibitory effect of humidity can be decreased by adding acrylate monomers. Epoxies stays in the liquid form while the acrylate creates a polymer network. Plasticizing effect of the epoxy monomers supports the chain progradation reaction by increasing molecular mobility. Acrylate polymers have higher molecular weight when cured with epoxies than just in pure acrylate monomer. Cationic photopolymerization reaction in epoxies is very sensitive to the oxygen while acrylates decrease this sensitivity and reduces the environmental impact on the cured material (Bourell, et al., 2017).

VAT photopolymerization has limited mechanical characteristics, but this technique has a high-quality surface and precision. Acrylates and epoxies have a range of typical resolution 50 – 100 µm (Ligon, et al., 2017).

The impact of laser beam plays a significant role in curing of the photopolymer that is directly related to the final product properties.

Printed prototypes are sometimes too soft or too hard and cannot be used for checking mechanical properties for the future mass manufacturing methods and applications of the product. This problem is caused by the laser beam failure (Jennings, 2018).

Resin needs right amount of energy to achieve solidification. If the material receives not enough UV energy or the laser is spending less time for curing process, then the print will not have appropriate characteristics to meet the application requirements (Jennings, 2018).

The most optimal solution is to decrease the speed of the printing modifying laser settings (Jennings, 2018). This process should be controlled and executed by the computer system since the machine can analyze and react faster than human.

The second problem is associated with the lack of appropriate amount of energy needed for curing process (Jennings, 2018). However, the AI system can modify the settings of the laser increasing energy gradually to avoid abrupt changes during the 3D printing process.

Critical exposure E_c to start the solidification is measured in and defined as (Ligon, et al., 2017):

$$E_c = E_0 \, exp\left(-\frac{C_d}{D_p}\right)$$

$E_c = Critical\ exposure\ (mJ/cm^2)$

$E_0 = Energy\ amount\ on\ the\ surface\ (mJ)$
$C_d = Curing\ depth\ (\mu m)$
$D_p = Penetration\ depth\ (nm)$

The penetration depth as defined by (Ligon, et al., 2017):

$$D_p = \frac{1}{2.3\varepsilon[I]}$$

$D_p = Penetration\ depth\ (nm)$
$\varepsilon = Molar\ extinction\ coefficient$
$I = Photoinitiator\ concentration\ (wt\ \%)$

Molar extinction coefficient (ε) and photoinitiator concentration $[I]$ are the most essential elements that affect the absorption of light at used wavelength.

Penetration depth is reduced by adding light absorbers which changes the formula (Ligon, et al., 2017):

$$D_p = \frac{1}{2.3(\varepsilon_I[I] + \varepsilon_A[A])}$$

$\varepsilon_I = Extinction\ coefficient$
$\varepsilon_A = Extinction\ coefficient$
$I = Photoinitiator\ concentration\ (wt\ \%)$
$A = Concentration\ of\ the\ absorber\ (wt\ \%)$

Penetration depth reduction is important for improvement of the resolution allowing creation of thinner layers.

Polymer cross-linking requires excess energy (E_x) to provide optimal strength which is needed for curing after 3D printing (Ligon, et al., 2017):

$$E_x = E_c \times \frac{D_p}{C_d} \times \left(\exp\left(\frac{C_d}{D_p} - 1\right) - 1\right)$$

$C_d = Curing\ depth\ (\mu m)$

$D_p = Penetration\ depth\ (nm)$

$E_c = Critical\ exposure\ (mJ/cm^2)$

$E_x = Excess\ energy\ (mJ/cm^2)$

Strength of the photopolymer can be increased in two ways (Ligon, et al., 2017):

- Lowering the penetration depth
- Increasing the amount of energy

UV absorbers increase the building time, but they improve resolution and strength.

This knowledge can be implemented in the creation process of the machine that can mix polymer during the curing process as well as for adjustment the UV laser settings to control the material curing and solidification process.

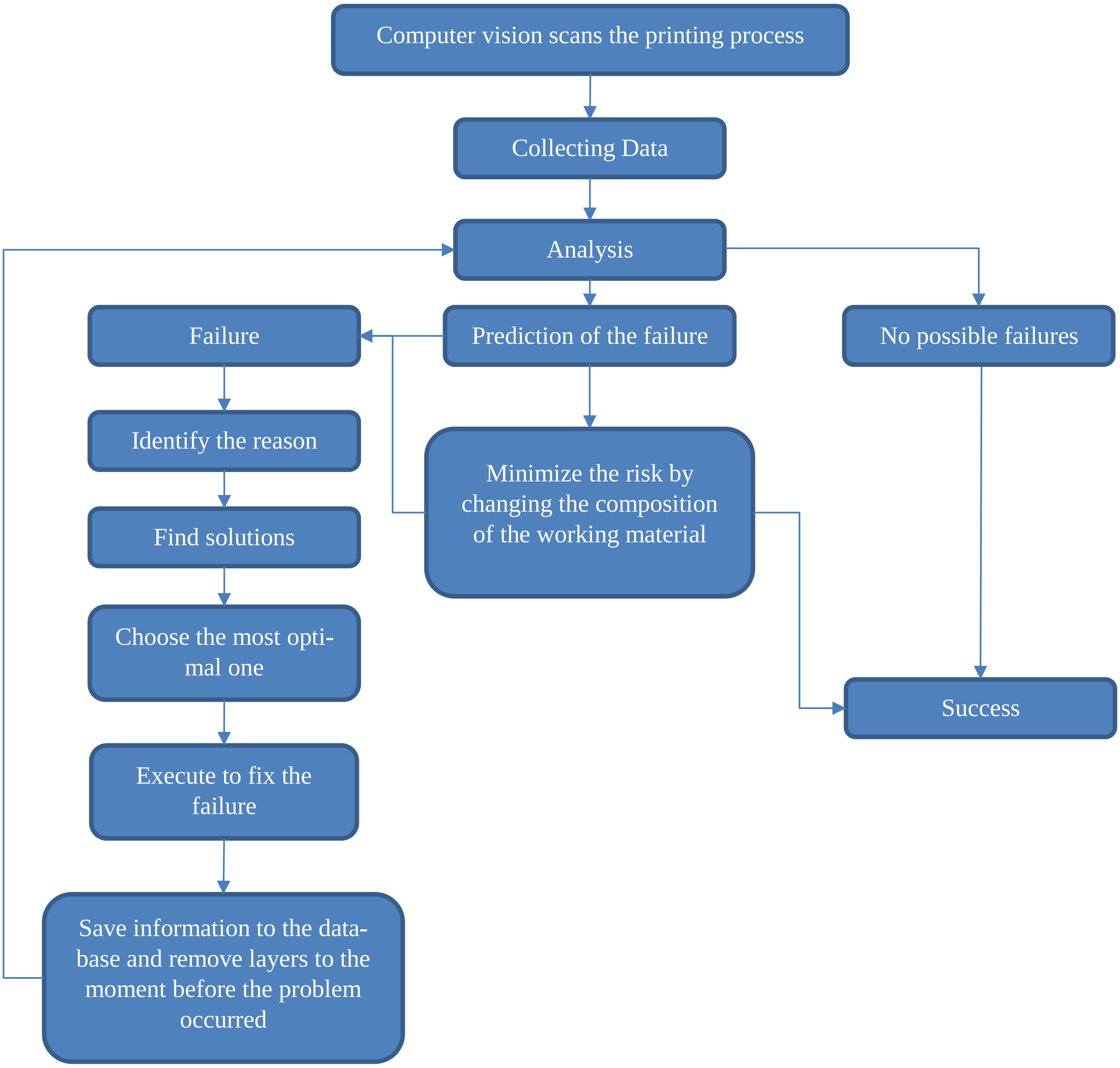

Figure 12. Photopolymerization reaction control system algorithm.

The required technologies include:

- SLA 3D printer
- Sensors
- CT scanning system
- Scanning cameras

- Invention that can inject particles of the photopolymer material separately from each other to change the composition of the working material. This machine should have vacuum inside to avoid oxidative degradation of the photopolymer.
- Adjustable laser
- Machine learning algorithm
- Software
- AI system

The required human resources:

- 3D printing engineer
- Sensors technician
- Automation CT engineer
- Laser and optics engineer
- Materials engineer with the deep knowledge of photopolymerization reactions.
- Machine learning specialist
- Data scientist
- AI research scientist

The desired control over the material properties during the printing process can be achieved with an invention of the machine that injects molecules such as monomers, oligomers and photoinitiators to change the composition of the working material and to control the future finished product properties. However, this should be done in vacuum conditions since the material is sensitive to the oxygen. Additional elements change the material properties till the end of the printing process. Also, laser settings can be modified based on the previously introduced formulas of the required energy from the laser to penetrate and activate initiators in the printing layer.

4 RESULTS

The new field of artificial intelligence has been studied to develop ideas about the improvement of the additive manufacturing process. Different SLA 3D printing problems have been identified during the visit to the Ajatec factory. General concept of the AI science was introduced with examples and solutions for the real-time 3D printing control. Plan for machine learning implementation was suggested. Concept of layer thickness control for the failure compensation was developed. AI system for the real-time printing control was created and explained with algorithms, required human and technical resources. Control over the quality and quantity concept was introduced. Sweeper self-control system was developed to avoid warping. Design support system concept was suggested for the future development. Theory of the photopolymers and photopolymerization reaction was represented with possible solutions of modifying laser setting and material properties. The necessary information to create solutions for the real-time 3D printing control was found, studied and produced in this research. The concepts were developed to solve each presented problem with different algorithms for machine learning and AI system.

5 DISCUSSION

Initial state of AI development was discussed based on the latest technologies and opinions of the AI experts. The main existing elements of data science, including machine learning and others, were explained in a clear way. 3D printing techniques were explained with unique features for each one. However, the research was focused on the SLA printing which theory and manufacturing process has been described most of all.

General concept of the AI system in real-time 3D printing control has been explained and developed with ML algorithms, that could be improved and implemented for the future projects. Planned equipment should be enough for the further research, but some parts can be excluded, while new necessary equipment should be added with the technological development to reduce costs and save time resources. Most of ideas are in the initial state and require serious development work, but the beginning of the development is created and can be used as a good start for the different projects and possible research works.

Required human resources were presented to create such a project. However, the project may require more proficiency for selecting necessary specialists, especially in the field of data science. The sphere of IT is quite complex, and the knowledge of the one data scientists may be very different from others. Therefore, the specification in the managing of human resources will not be superfluous with additional knowledge of experts. Theory of the photopolymerization process was explained and implemented for the solution of SLA 3D printing control methods. Ideas require development and improvements, but in general, the general information is presented clearly and contains interesting solutions.

6 CONCLUSION

The main perspective way of artificial intelligence implementation in the world of additive manufacturing technologies is based on the 3D printing process development and bringing the design process to the new level. Therefore, the implementation of artificial intelligence in additive manufacturing has been represented with the existing and developed solutions. AI working system concept has been explained. Control over 3D printing properties has been introduced with created algorithms. Required human resources have been described. Necessary equipment has been introduced.

AI science has been used to solve the problems of analysis process before the printing procedure to reduce risks of failure. Another interesting part is the further development of the digitalization process allowing user to solve the failures in the printing process with an AI system without asking for service support. This feature simplifies the supply chain and the production process. Machine learning improves the printing quality reducing risks of failure and manufacturing waste. The recycling in the field of additive manufacturing should be minimized with zero waste production. Also, there are a lot of possible ways which can be developed to protect the printing data and digital security system due to AI technologies.

The nearest future of the interaction between the artificial intelligence and additive manufacturing depends on the machine learning development. Elements of mechanisms and tools should be 3D printed and transported to substitute failed parts that will lead to the reduction of spare parts costs and transportation expenses, and improved customer experience (Krauss, 2017).

The importance of this study is valuable for the future development of AM technologies, especially SLA 3D printing. This thesis covers all parts of possible cooperation of AM and AI system with detailed instructions. The AI system with computer vision can be easily developed based on the presented solutions.

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