Automated lay-up of carbon fiber reinforced polymers is an established method for producing large parts in the aerospace industry. Currently, the quality control for this automated manufacturing process is performed by humans. In the last years, research has focused on increasing productivity of automated lay-up, thus the automation of the quality control has been taken into consideration. The objectives of the paper are to review the requirements for quality control based on an overview of the possible defects in automated lay-up and to evaluate their fulfilment by both visual quality control by humans and automated quality control systems.

A literature review of quality control for automated lay-up processes of CFRP

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Literaturübersicht zur Qualitätskontrolle von automatisierten Ablegeverfahren von CFK

Automatisiertes Ablegen von kohlenstofffaserverstärkten Kunststoffe ist eine etablierte Methode zur Herstellung großer Flugzeugteile. Zurzeit wird die Qualitätskontrolle dieses automatisierten Fertigungsverfahrens noch von Menschen durchgeführt. In den letzten Jahren hat sich die Forschung auf die Automatisierung der Qualitätskontrolle fokussiert um die Produktivität zu erhöhen. Die Ziele dieser Literaturübersicht sind, die Anforderungen für die Qualitätskontrolle basierend auf den vorkommenden Fehlern festzulegen und die Erfüllung dieser Anforderungen durch die visuelle Qualitätskontrolle durch den Mensch als auch durch automatisierte Systeme zu bewerten.
A literature review of quality control for automated lay-up processes

K. Schlegel, P. Parlevliet, C. Weimer, A. Schuster, M. Kupke

1. INTRODUCTION

The development of automated lay-up of carbon fiber reinforced polymers (CFRP) derived from the need to efficiently produce large aerospace parts [1], such as the skins of the fuselage and wing covers [2-3]. Cincinnati Milacron introduced the first commercial ATL (Automated Tape Laying) machine, laying up 75 mm, 150 mm or 300 mm wide tape of thermoset prepreg [4-6]. Before the material is placed, the substrate is heated up and the material is subsequently tacked on the substrate with a compaction roller. AFP (Automated Fiber Placement) machines followed as a logical combination of ATL and the Filament Winding Process, placing up to 32 narrow tows with a width of 3.2 mm, 6.4 mm or 12.7 mm ($\frac{3}{8}$", $\frac{1}{4}$", $\frac{1}{2}$") of thermoset prepreg at the same time [5,7]. These lay-ups are subsequently cured in an autoclave [1,8]. The process of laying up thermoplastic prepreg can be referred to as Thermoplastic Composite Automated Fiber Placement (TPC AFP) [9]. Recent developments include Dry Fiber Placement (DFP) by placing fiber tows that are held together by a polymer binder to reduce material costs [6,10] or Automated Dry Material Placement (ADMP) where wide fabric sheets are placed to increase production rates [10-1]. These lay-ups are later infused with resin and cured [10,12].

Compared to manual lay-up of wide tapes, automated lay-up can produce parts at rates 10-20 times faster [13-14]. The productivity of AFP can reach up to 45 kg/h-62.4 kg/h [5,15-16], but that strongly depends on the complexity of the part and on the material. For the aerospace composite market, the forecasts state that by 2020 around 50 % of composite manufacturing will be performed by AFP and ATL machines, compared to the current approximately 35 % [17]. Even though AFP and ATL are considered fast and efficient processes, due to the idle times of the machine, e.g. during visual quality control, the production with these machines is not necessarily efficient [18]. Looking at planned production rates of up to 60 Airbus A320 per month in 2020 [19] compared to the planned 10 Airbus A350 per month for the end of 2018 [20], more machines are necessary and productivity has to be increased. An AFP machine is a large capital investment of typically more than US$ 5 million [5-21], so a main objective is to make the machines more profitable.

Hence the question is how the productivity of the automated lay-up process can be increased. Machine manufacturers are focusing on accelerating the maximum speed from 1 m/s to up to 3 m/s [22] and placing wider material of up to 2" [23] compared to the commonly used $\frac{1}{4}$" and $\frac{1}{2}$" for AFP. Another
emphasized, which this paper focuses on, is the decrease of idle times of the
machine by automating the quality control of the lay-up [23].

The need for automated quality control to detect defects in the lay-up has been
stated frequently [24-28]. Although reviews are available on automated lay-up
processes [5,13,28-29], quality control is rarely mentioned. A short overview of
quality control technologies and the few existing systems has been published
[26]. However, there is neither a review on the state-of-the-art quality control for
lay-up processes nor on the potential technologies for automated quality
control. Various publications are available with different technologies, ranging
from camera-based systems [30] to systems working with Eddy Current Testing
or compaction measurements [31-32]. However, the requirements vary and only
few comparisons between different technologies are drawn.

To fill this gap, this paper first analyzes the defects that can occur during the
automated lay-up process in order to derive the requirements for quality control
with a focus on defect detection. By these requirements the currently applied
quality control is evaluated. Due to the industrial nature of the topic, there is a
lack in scientific publications, consequently, images, videos and press releases
are included as sources of information. The different types of quality control are
identified before the existing technologies for automated quality control systems
are presented and evaluated according to the fulfillment of requirements. Due to
its industrial relevance, the main focus is the quality control of AFP, while the
few existing references to DFP and TPC AFP are also included.

1.1 Defects in automated lay-up

Automated lay-up can place tows with a higher accuracy and with a better
repeatability compared to manual lay-up [1,13,33]. But even with an automated
process lay-up, anomalies occur [14,34]. While the term ‘anomaly’ is used for
any deviation from the desired lay-up, the term ‘defect’ is used when the
deviation surpasses a certain tolerance. Therefore, not every anomaly is
considered a defect that requires further action. The manufacturer of the part
defines the tolerances that determine whether an anomaly is classified as a
defect [35].

There is a multitude of types and names for anomalies with Gap, Overlap,
foreign anomalies, Wrinkled Tow and Twist being the most typical ones [32-39].
In the following section, the most common types of anomalies are divided into
the four categories: imprecise positioning, improper bonding, foreign anomalies,
and tow anomalies, see Table 1 and Figure 1.
**Imprecise positioning**

Ply boundary (1) deviations include tows that were cut too late or too early or that were added too early or too late [35]. The term Edge of Ply (EOP) is also common [18,40]. Imprecise positioning can create a Gap (2) [6]. Different tolerances for Gaps are defined as they can occur in between the tows of one course or in between two adjacent courses, with a course being defined as all the tows the machine lays up at once [41-42]. Also, a cumulative Gap defect exists where all the Gap sizes are measured across a ply [35-43], and Gaps can be desired Gaps of 0.5 mm – 1 mm to prevent Overlaps (3) [5,44]. Furthermore, an Overlap [6,32] between parallel adjacent tows can occur. Several American sources [14,30,45-46] use the term Lap instead of Overlap. It can also occur that a tow gets twisted (4) [39] or folded [47]. A tow can be missing (5) completely, or be dropped (6) during the lay-up.

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**Table 1: Types of anomalies (Numbers for further referring in the text)**

<table>
<thead>
<tr>
<th>Imprecise positioning</th>
<th>Improper bonding</th>
<th>Foreign objects</th>
<th>Tow deviations</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Ply boundary (Early/Late Add/Cut)</td>
<td>7. Loose Tow</td>
<td>10. Fuzz Ball</td>
<td>13. Splice</td>
</tr>
<tr>
<td>3. Overlap</td>
<td>9. Bridging Tow</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. Twist</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5. Missing Tow</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6. Dropped Tow</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Figure 1: Types of anomalies**
Improper Bonding

Bonding problems can lead to a Loose Tow (7) and excessive steering can result in a Wrinkled Tow (8) [48]. Tow bridging (9) [49] can occur when placed over an internal radius [50]. Entrapped air pockets are also phenomena that can be caused by bonding problems [39].

Foreign anomalies

A Fuzz Ball (10) is an accumulation of loose fibers or resin build-up [51] and is considered a foreign anomaly. Glove pieces, washers, backing film [52] or foil [31] are examples of Foreign Object Debris (FOD) (11) [49]. Contamination (12) [31] is not further specified in literature, but could be any liquid, such as water, oil or hard grease [53].

Tow anomalies

The joining of two overlapping tow ends to a so-called Splice (13). According to DIN 29971 [54], one single spliced tow is not considered a defect if its overlapping area does not exceed 12% of the tow width, if no more than 3 Splices occur in 8 m of consecutive tow length and if their distance to each other is not less than 1 m. In one ply, Splices that are located within 304.8 mm (12") to each other are considered a defect [18]. Tow anomalies include the variation of the tow width (14) [55].

Sources for these anomalies during the automated lay-up process can be:

- The manufacturing process of the material, e.g. tape slitting causing Fuzz Balls (10) or differences in tow width (14) [6,51].
- The guidance of the material in the AFP machine, e.g. friction over the rollers causing Twists (4) [22,51] and Fuzz Balls (10) [40].
- The AFP process itself, e.g. machine tolerances and steering, which can result in Gaps (2) and Overlaps (3) [38,50].

For the 14 defect types in Table 1 and Figure 1, only one publication on numbers for defect rates was found. A part study [27] from a machine supplier investigated the defect rate for Dropped Tows (6). Dropped Tows occurred on average:

- once in 3000 individual tows
- once every 1.5 hours of part build time or 30 min of machine run time
- in total less than 60 times during a part build with a total of 167,539 tows

Those 60 Dropped Tows and all other defects have to be detected by quality control and then be reworked [27]. Rework is considered as the act of removing a tow [56] or section of the faulty lay-up and replacing the missing section with new tows. Removing is done manually, by pulling the tows from the lay-up. To remove sticking Fuzz Balls a cutter knife is used [56].

After cure, a non-destructive inspection (NDI) is performed that is commonly based on ultrasound [57,58]. A C-scan provides a two-dimensional top view of a
section and irregularities can be determined within the part, such as porosity or delamination. These irregularities could be the result of defects in the lay-up process, but on the cured part, rework is not possible anymore and an expensive repair or scrap are the only options [39]. For this reason, it is crucial to detect the defect during the lay-up process. Especially as the mechanical properties of the part can be negatively influenced by these anomalies [59], e.g. it was shown that a Gap or Overlap can reduce the strength up to 27% [60].

1.2 Requirements for quality control

The term quality control is product-oriented, focusing on defect identification. Quality control is part of quality assurance which is process-oriented with the aim of defect prevention. The first step is to have a quality control system which later can be enhanced into a quality assurance system. [61]

Requirements for quality control systems for automated lay-up are:

- Reliable and robust detection of defect with accuracy of location
- Minimum of time-consumption
- Negative interference with lay-up process

The baseline of quality control for automated lay-up is a customer- or even a part-dependent defect specification that lists the defect types as discussed in section 1.1. Defect detection has to be able to determine if a detected anomaly is within the tolerances and therefore insignificant or if the size of the anomaly surpasses the tolerance and is therefore considered a defect. Also, it is crucial that the defect can be located with the needed accuracy. Defect detection needs to be robust, e.g. concerning the conditions on the shop floor, such as ambient light, humidity, temperature, vibration and contamination.

With the focus on increasing productivity of the automated lay-up process, the time needed for quality control has to be kept as low as possible. Additionally, quality control should preferably not impact the lay-up process, e.g. by reducing the lay-up velocity or by changing the lay-up paths due to geometrical interference.

2. STATE OF THE ART QUALITY CONTROL IN PRODUCTION

2.1 Visual quality control by humans

For the quality control of the AFP process, the current standard of the aerospace industry is to have a visual inspection performed by dedicated personnel throughout the world today [14,21-27], although there have been
Each tow of every placed ply has to be visually inspected for the defects in Figure 1 and Table 1 before the next ply can be laid up. Instruments to manually measure whether a detected anomaly is considered a defect include a calliper, a ruler or a pocket scale [21,42-43,63]. For the manufacturing of large parts, the inspector has to walk along the part [35] or even has to climb onto the part for further inspection and possible rework [63]. For certain parts the inspector has to use a platform in order to be able to inspect all sections of the part with additional rotating of the part during the inspection [63]. Up to six inspectors can be needed to inspect large parts with loupes and flash lights, while wearing safety glasses [14,56-57,64]. Based on these sources, the authors assume that this quality control is vulnerable to human error due to different perception of each inspector and the lack in repeatability. Therefore, there is no certainty that all defects are detected.

Besides the uncertainty due to the human factor, there are differences in the inspection procedure. One difference is the person who is performing the inspection: In European sources, the machine operator will also perform the quality inspection and remove defects [39]. In sources from the US, a second person, referred to as part inspector, performs a final inspection after each ply to ensure the quality before another ply is placed [27]. While the inspection by a second person requires additional resources, the probability to detect all defects is increased by a second pair of eyes. Another difference between sources is the frequency, respectively timing, of the inspection process. Most sources state that there is an inspection after each ply [65]. Others refer to an inspection after each sequence [66] or use the term ply sequence [14]. A sequence comprehends all the plies with the same orientation of one layer [51]. While an inspection after every sequence is sufficient to inspect all the plies of the sequence, an inspection after every ply allows an earlier action in case of unacceptable lay-up quality. However, more inspecting also results in a more inefficient production process, because the placement process must be stopped and cannot continue until the inspection is completed, adding to machine idle time [39].

Breaking down of the floor-to-floor times (the total time the tooling is located in the AFP cell) of comparable parts, reveals considerable differences in inspection times: In 2012, Boeing and MAG [25] published a study on an overall process improvement with e.g. an increased spool size and a new maintenance routine [25]. When comparing the baseline process in Figure 2a to the improved process in Figure 2b, the actual time to inspect the same part was almost cut in half, while the relative proportion for inspection is 10 % higher. In 2014, Electroimpact [27] published a similar study, see Figure 2c, based on a larger fuselage barrel that was produced in less time than the fuselage in Figure 2a-b. The fraction of time spent for inspecting a bigger part is less. While the reason for these differences in inspection time cannot be correlated from the given information, it can be assumed that quality control performed by one human might not be comparable to another one.
The defect detection is not reliable as the inspector has to visually inspect for defects and manually measure their size and position. This needed time for visual quality control varies between 14% and 47% of the floor-to-floor time [26] which can be more time-consuming than the lay-up process itself. Therefore the requirements of quality control as discussed in section 1.2 are not fulfilled.

2.2 Human monitoring by camera and assisted visual inspection

Soucy [46] reported a camera system mounted on the AFP head. Thereby, the operator is able to do a continuous monitoring of the tows currently being laid on a display. However, this demands a high degree of concentration due to the little contrast that the CFRP shows, thus it is not sufficiently reliable to substitute the inspection after the ply lay-up is finished. Assisted visual inspection was the first advancement towards the automation of the quality control. The inspector performs a visual inspection with the assistance of projections from a laser. Cemenska [35] stated that laser projectors have projected ply boundaries for visual inspection for decades. In 2012, Rudberg [68] introduced a laser projector that had been integrated into the reference system of the AFP machine to visualize Ply boundaries by projecting them onto the ply surface. The operator or inspector verified the accuracy of the tow placement by visually comparing the location of the end of the tow with the projected laser lines. The system has been further developed to also project individual courses, tows, their numbering, and 3-D points to help the inspector determine to which course a missing tow belongs [27,35,68]. Further desired Gaps and Overlaps were visualized [26]. While the laser projector can support the inspector, only the Ply
boundary and desired defects can be projected. The uncertainty due to the human factor and the time consumption remain.

3. AUTOMATED QUALITY CONTROL SYSTEMS

The next level is the automation of quality control. To give an outlook to what can be accomplished with automated quality control for defects in the lay-up, the automation of the calibration procedure of the AFP machine is an excellent example to show the difference in accuracy and inspection time between manual and automated measurements (see Table 2). In order to achieve high placement accuracy at high speeds, the timing of feeding and cutting tows has to be adjusted to minimize Ply boundary defects.

<table>
<thead>
<tr>
<th></th>
<th>Manual</th>
<th>Automated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurement error</td>
<td>0.02 inch</td>
<td>0.01 inch</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>0.007 inch</td>
<td>0.005 inch</td>
</tr>
<tr>
<td>Measurement time</td>
<td>25 min</td>
<td>2 min</td>
</tr>
</tbody>
</table>

*Table 2: 114 measurements of tow end position of a 16 tow machine for calibration [42]*

Until 2011, this calibration had been performed manually. To do so, several test patches were placed with various feed rates and the beginning and end of each tow was measured with a digital micrometer, caliper or loupe. Then the tow placement error could be compensated by adjusting the timing of the feeding and cutting of the tows [42]. In 2011, Cemenska [42] introduced a laser system to determine the beginning and end of the tows by the intensity of the reflection of the laser light. By automatizing this step, a minimization of machine idle time and an improvement of measurement accuracy were accomplished, while the factor of variation due to human error was eliminated.

3.1 Types of quality control systems

The terms ‘monitoring’ and ‘inspection’ are linked to quality control. ‘Monitoring’ [12,38,45,66,69] is frequently used if the quality is looked at continuously during production, such as monitoring by camera when a person looks at the camera constantly. ‘Inspection’ [14,21,30,49] more often defines an act of looking at the quality as an ad-hoc [70] step, therefore at a certain state after a production step. Aside from these, there is a frequent use of the terms ‘inline’ [71-73] and ‘online’ [74-75], also called in-process [46,76] or rarely in-situ [32], quality control. Online control, compared to inline control, is characterized by a shorter
time frame between sampling and analyzing of the results. With online control, the time frame is short enough for the material properties not to change significantly, which allows an immediate corrective action [77]. When transferring this definition to the lay-up process, online control or monitoring [38] [39,66] takes place during an inline control or inspection [37,78-79] after the placement process.

**Online monitoring during lay-up**

Online monitoring takes place at the same time as the placement process, thus in parallel, making an immediate action possible to prevent further damage, see Figure 3. As the current maximum lay-up velocity of the machines is 1 m/s, an online quality control system has to be capable of working at the same velocity. This results in a possible quality control time reduction of nearly 0% of the floor-to-floor time. An online monitoring system can be directly mounted on the lay-up head [14]. Depending on where the system is mounted, there is a further differentiation possible for online quality control systems by the point of measurement:

- **A nip-point** system (Figure 3a) measures at the point or closely to where the material is being placed, e.g. compaction measurements of the roller and Fiber Bragg Grating sensors in the lay-up. Defects can be detected at the moment when they occur, while there is no interference of the lay-up head with e.g. concave parts.

- **An overrun** system (Figure 3b) is located behind the placement process, a few centimeters behind the compaction roller, and measures a few seconds after placement. Depending on the size of the system and the complexity of the part, there might be a geometrical interference with the tooling. Nonetheless, the distance of the measurement point to the nip point should be as small as possible. With a higher distance, the risk increases that during steering the measuring point is not on the lay-up anymore. Further when the machine is tilted, a camera will not have the optimal distance to the lay-up anymore and be out of focus.

- **Monitoring of the incoming material** (Figure 3c) is a part of online quality control, where the quality of the material can be monitored while the tows are guided through the machine head and thus before placement. Torres [80] patented detector photodiodes within the tape laying unit for monitoring. Although it is not explained how defects are detected, the further lay-up is stopped and instead the affected material section is placed on a scrap table [81]. Ingersoll [82] reported a similar system for monitoring of the incoming material. Defects such as Twists, Splices, Dropped Tows, Missing Tows, and the tow width can be measured and the location of the defect is communicated to the inspector after the ply is finished for rework [26].

- **Monitoring systems can be in the forerun** (Figure 3d), meaning in front of the placement process. By edge detection of the last course, Gaps and Overlaps can be avoided with a path correction [66].
Nip-point and overrun monitoring are able to detect most defect types. Monitoring of the incoming tow is neither capable of detecting position nor bonding defects as they occur during the placement, but small FODs that will be underneath the surface might only be detectable prior to placement. Similarly, a forerun system can only be an add-on to a nip-point or overrun system as only Gaps and Overlaps can be avoided.

**Inline inspection after lay-up**

Inline inspection results in an additional process step and takes place immediately following a production step, in the case of AFP process, after a ply is finished [83]. The inspection system is moved along the part in order to capture all the information necessary to detect defects, while the lay-up machine is idle. The system can be mounted on the AFP head, or on a separate gantry or robot as a stand-alone system, see Figure 3. While automated inline inspection after the lay-up of a ply is the substitution of the visual inspection by humans, continuous online monitoring during lay-up saves formerly inspection time.

![Figure 3: Online monitoring a) nip-point b) overrun c) incoming tow d) forerun and inline inspection](image)

### 3.2 Technologies for quality control systems

The first patent for an inspection system for automated lay-up was filed in 1994 [84], and in 1996 the first research results of an inspection system were presented [85]. While the number of filed patents increased over the following years, an increase in research publications on inspection systems did not occur until 2013, Figure 4. Airplane manufacturers, especially Boeing [84,86], hold most of the patents. Most publications were part of research projects [87], but machine manufacturers have also worked on quality control systems, e.g. MTorres [88] and Ingersoll [89].
While most publications and patents are based on the camera-based systems 2D imaging, 3D scanning, infrared thermography, see Table 5, a few other technologies and hybrid systems combining several technologies [30,66], have been considered as well. While 2D Imaging can use illumination to enhance the image, 3D scanning needs a laser as a light source to acquire 3D information. Those two technologies differ from infrared thermography, where an image of invisible, infrared wavelengths is taken. The camera-based technologies, ultrasound and Eddy Current testing are contactless technologies, while Fiber Bragg grating sensors require to be implemented into the lay-up and remain there [32]. Although online monitoring is the goal in most studies, the change from visual quality control by humans to automated quality control occurs gradually, therefore most systems were first directed at inline inspection and were later developed into online monitoring systems [14,83].

In the following section, the technologies are explained in more detail and automated quality control systems using those inline and online technologies are reviewed along the discussed requirements. Table 5 gives an overview of the mentioned automated quality control systems.

![Figure 4: Patents and publications for automated quality control systems for lay-up](image)

2D imaging

In 2005, Engelbart [90] first described a camera capturing 2D images of a ply in order to detect defects. Compared to human monitoring by camera on a display (see chapter 2.2), the detection of defects is automatically performed by image analyzer software [35].

Shadmehri [49] described a system that projected inspection features such as Ply boundary, tow angle or gap size onto the part with a laser. Then the camera captured an image of the lay-up and the projected inspection feature. The inspector received the image of the inspected feature on a screen and decided if rework was needed. Cemenska [35] introduced a system working with the camera on a laser projector. A feature recognition software measured the Ply boundaries and verified that they were within tolerances (see Figure 5b). Out-of-tolerance features were reported to the user interface. Cemenska [30] stated
that 2D imaging was proven to correctly identify and measure 92% of the Ply boundaries. Tow ends that were not identified by the software were forwarded to the user interface for semi-automatic detection [30]. The inspector was provided with both an image of the defect and a view of the defect location [35]. Tow ends that were trimmed from the final part did not get imaged [30].

Defect detection capabilities of this technology were shown to provide very good results for some of the defects. The image quality depends on the optical properties of the CFRP material. CFRP reflects light mainly in one direction instead of diffusively, resulting in images with poor contrast. Thus the parameters of the imaging system have to be adapted to the part being manufactured, requiring an intensive illumination and complete image analysis [30]. Different types of illumination, e.g. dark field illumination [86], are possible to enhance the image quality. The camera can either work as an inline inspection system [49] by taking images after the lay-up of one ply is finished, or online with the camera mounted on the lay-up head to already start capturing images during material lay-up [35], see Figure 5.

![Figure 5: a) Setup of camera for online monitoring b) Image of Ply boundary identification [30]](image)

**3D Scanning**

In 2010, Hunter [91] first described a 3D scanning method for the quality control of automated lay-up. A laser beam is projected from a certain direction onto the surface of the object. The diffuse reflection is observed by a camera from a different direction, see Figure 6a. The angle between both directions is called the angle of triangulation. By using special lenses, the incoming laser beam is fanned out to form a laser line. From the shape of the laser line on the surface, the distance can be calculated. As a result, the height of the surface along the laser line can be determined. By moving the system along the surface, a 3D scan of the object is created [92-93].

There are contact, transmissive or reflective methods for 3D scanning [94]. The technology described is a reflective technology that uses electromagnetic radiation, therefore is considered an active method compared to passive...
methods that work without directed illumination [92]. Several systems using this technology for the quality control of AFP are known (see Table 5) although different names are used. Two systems originating from Europe use the term 'laser triangulation system' [83] and 'laser light section system' [66], while systems from the US are referred to as 'laser line scanners' [14] or 'laser profilometers' [35].

It has been shown that the laser triangulation technology can be used for inline inspection [14] [83]. For scanning single-curved surfaces or double-curved surfaces, a 3D guidance system, e.g. a 6-axis-industrial robot, is necessary [83]. The camera, mostly CMOS (Complementary Metal Oxide Semiconductor) [66], acquires the profile of the laser line projected on the lay-up surface after each ply is finished. Maass [14] reported that scanning of one ply of a 2” x 2” (50.8 mm x 50.8 mm) flat panel takes 5 to 10 minutes. The technology also works for online monitoring by mounting the system in the overrun of the lay-up head itself and monitoring each ply during lay-up right behind the compaction roller [35]. A laser triangulation system with a scanning frequency of 1 kHz, allowing the measurement of a defect’s position with a tolerance of 1 mm and lay-up velocities of up to 1 m/s, was successfully tested [83]. With the three-dimensional coordinates that the system acquires, a point cloud is created. From this topology, specific algorithms, e.g. in Matlab [14], detect geometrical lay-up features like tow edges and categorize them in different defect types. Cemenska [30] investigated profilometers with a low scanning frequency to specifically detect Gaps, Overlaps, FODs and to measure the tow width. The minimum length of a defect must be 0.5” (12.7 mm) with a surface height of 0.05” (1.27 mm). Detection of defect types that are not detectable by humans, e.g. cumulative Gap, are possible [35]. For visualizing the defects and their location, different approaches have been presented:

- A color scale represents the Z coordinate [14], see Figure 6b,
- different colors are assigned to specific defect types [83], or
- measurements that violate the acceptable limits are displayed in red, while measurements that approach the limits of acceptance are displayed in yellow [35].

Visual inspection by humans can be substituted or minimized by identifying areas with possible defects by 3D scanning and asking for further examination by the inspector when necessary [66]. The system delivers a feedback in real-time, so the inspector has already the chance to evaluate defects on a PC before the lay-up is completely finished [95]. Cemenska [35] described a user interface based on an interactive 3D model with the part images overlaid in real-time showing the part itself, defects and coordinates. The inspector can observe all inspection data of several machines and decide if rework is necessary. The exact position of the defect on the part can be shown with a laser projector. For the future, augmented reality is under discussion [96]. The measurements are stored in a database including part- and manufacturing-specific information [35]. With this data, a statistical process analysis is enabled.
A laser triangulation system allowed the detection of 11 out of the 14 specified defect types, see Table 3, as an online monitoring system. The defect types Loose Tow and tow width were not tested within the found publications. Contamination needs to be further specified in order to verify defect detection capabilities. This 3D scanning technology is also camera-based, consequently the same limitations as for 2D imaging apply. Further, regions of different thickness and complex subsurface geometries with Overlaps and Gaps lead to wrong defect interpretations concerning the distinction between tow ends and Splices [14]. Due to the needed triangulation angle, the system cannot be placed close to the compaction roller. Distances of 100 mm to the lay-up point were reported [83]. The angle and distance between the laser triangulation system and the lay-up surface changes as the AFP head moves along complex surfaces and the laser triangulation system might not be directed towards the part at all times. Although there are low cost systems off the shelf available [14,18], costs are still estimated at US$ 20,000 per system and, depending on the length of the laser line, up to 7 systems are necessary to scan a lay-up width of 24 x ½” (24 x 12.7 mm) [30]. The total investment is estimated at US$ 150,000 [67]. Additionally, the integration of the 3D scanning systems into the lay-up head is expected to require 2 engineers for 1 year and 1 year of support, because parameters of the imaging system such as laser output power depend greatly on the parts being made, and a system that works for one part might not work on a different part, e.g. the different prepreg material or geometry of part [30].

![Figure 6: a) Setup of 3D scanning system b) Height profile with color scale of several tows [14]](image)

**Infrared thermography**

Ritter [97] patented the first system with infrared cameras for online quality monitoring in 2005. Infrared thermography can determine the surface temperature of an object based on its thermal energy as objects with a temperature above 0 K emit electromagnetic radiation in the infrared spectrum (wavelength of 0.75-1000 µm) [98]. With an infrared detecting device, for example an infrared camera, the thermal energy radiated from the object in the
Infrared spectrum is detected and a surface temperature map can be created [99]. An image analyzer algorithm evaluates the temperature map to detect specified properties like edges or anomalies [97].

The camera's field of view can be behind the compaction roller as shown in Figure 7a, where the thermal contrast is at maximum, since the recently placed cold tows exhibit a lower temperature than the surrounding heated mold or earlier placed tows [39], see Figure 7b. The software [39] compares the thermal image to a baseline thermal image with the expected normal temperature distribution picture. Hotter or colder spots are easily detectable and show the existence of anomalies [100]. The temperature of the tow can also indicate the quality of the bond [39]. Within the laid up tows, differences in the surface temperature indicate differing thermal properties of the material, which indicates FOD [22, 52, 97, 101]. Defects like Missing Tows [100], Wrinkled Tows and other bonding defects can be detected as well [97]. Similar to the other image-based systems, the inspector sees the image, or the data is sent to a laser projector for the projection of the defect's location onto the composite material surface.

Ritter [97] described a system with 8 infrared cameras for a 24" (609.6 mm) wide lay-up for a lay-up speed of 10 inch/s (0.254 m/s). An edge detection algorithm is applied for positioning defects and, separately, a surface inspection algorithm is applied for bonding defects. With Labview software, image analyzing was shown to work for real-time processing [97]. From the measured temperature differences, the image analyzer algorithm detects the edges of the tows and consequently their position [97]. Denkena [39] revealed results using this technology with a resolution of 7 pixels/mm with a velocity of 1 m/s, but stated that real-time capabilities were limited by the camera. For a gap bigger than 0.7 mm, the surface radiation through the gap will result in a local temperature maximum, while Overlaps result in a local temperature minimum [52], see Figure 7b. A special use of infrared thermography was described in [101], where an infrared heat source heats up the prepreg again after it was laid up. The heat source is placed 100 mm behind the compaction roller and the infrared camera another 100 mm behind that for the purpose of online monitoring.

Although infrared thermography shows good defect detection capabilities, especially for bonding and foreign defects [102], defect size and the accuracy of the defect's location was rarely investigated. Due to fewer geometrical restrictions compared to 3D scanning, the point of measurement can be closer to the nip point. Although the lay-up velocity does not significantly influence the heat-up behavior, a temperature model to forecast the temperature distribution for certain process parameters is necessary as a basis for reliable and robust thermal online monitoring [76].
Compaction measurement

Belhaj [12] suggested online monitoring of the force applied by the compaction roller in order to identify defects in 2013, Figure 8a. A force torque system is often already integrated in the lay-up head to monitor the force of the compaction roller during lay-up, as it is also an important parameter to avoid air pores, bridging effects and to increase tack characteristics [66,69].

A study on various placement patterns with dry fiber tows was conducted with a compression test. For that purpose, lay-up samples were manufactured with positioning defects such as a Gap and an Overlap of 2 mm [12]. It was shown that the Gap and the Overlap show specific characteristics related to fiber fraction as shown in Figure 8b [103].

Defect detection capabilities have not been tested with an online monitoring system, and the definition of an accurate model for every part would require an extensive experimental program, involving studies of different placement patterns and defects. Further, online visual control might be necessary for complementary defect detection or to clearly define the type of defect [12]. As a force torque system is usually already integrated in the lay-up head, no further device that causes interference with the lay-up head is necessary. Additionally, the entire placement history of the lay-up can be considered and not just on ply level. Newly laid up tows might compensate an unwanted Gap with the result of making the lay-up acceptable again.
Ultrasound

In 1999 Djordjevic [85] tested an ultrasonic remote inspection system on laid up thermoplastic prepreg to detect consolidation defects, see Figure 9b. Ultrasound consists of sound waves with frequencies above 20 kHz, which is higher than human hearing. The contact-based ultrasonic C-Scan technique as used in NDI cannot be applied to uncured material due to the necessity of a coupling agent such as water [104].

The detection of delamination in prepreg was studied with a non-contact laser-generated ultrasonic technique and an air-coupled transducer [65]. A line scan technique was used to confirm the capability as an inline application (see Figure 9a). Signal characteristics caused by defects were analyzed and parameters to determine defect regions were found [105].

The ultrasound technology has not been tested concerning the detection of defects as specified in this paper. It has been suggested to place an ultrasonic system above the compaction roller as a nip-point system, but the capability was not shown.
Eddy Current testing

Studies [106] have been conducted to show the capabilities of Eddy currents for defect detection in dry preforms. In 2014, Schmidt [31] investigated high frequency Eddy Current testing for online quality control of AFP parts. Eddy Current testing is based on electrical properties of a conducting material. A coil with alternating current is placed over the material, and by electromagnetic induction, eddy current flow is induced into the material. The current generates an alternating magnetic field which can be detected by another coil, see Figure 10a. For multi-layer components and maintenance inspection of aircrafts, Eddy Current testing is already in use. The Eddy Current is affected by the conductivity of the material and magnetic permeability. Any defects or discontinuity in their material disturb the eddy current flow [107,108,109].

Uncured prepreg was tested and the measurement speed was theoretically calculated to be as high as 0.07 m/s. Defects such as FODs and Fuzz Balls were detectable in a depth of up to 7 mm, as well as Gaps and Overlaps as shown in Figure 10b. Additionally, subsurface flaws can be detected, such as Fuzz Balls or FOD underneath a tow [31].

Eddy Current Testing was capable of detecting some of the specified defects (see Table 3), but without information about the size of the defect and the accuracy of the defect’s location. Due to the limited measurement speed, an online quality control system is not possible at the moment.

![Eddy Current setup and visualization](image)

*Figure 10: a) Setup of the inline eddy current quality control b) Visualization with Eddy Current of Gaps (running from left to right, hardly visible) and Overlaps (running from top to bottom) [31]*

Fiber Bragg grating

Oromiehie [32,38,110] has been investigating Fiber Bragg grating (FBG) sensors for online monitoring during lay-up since 2016. The Fiber Bragg grating technology consists of an optical fiber with a periodical reflective index along the longitudinal direction of the fiber core creating a wavelength-specific dielectric mirror. This specific wavelength is called the Bragg wavelength $\lambda_B$. When strain or temperature is induced, the FBG reacts accordingly, causing a proportional

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Schlegel, Kupke et al. Quality control for automated lay-up

shift in the reflected Bragg wavelength [111, 112]. Measurements in composite material have been performed at a wide range [113]. The first step towards monitoring the AFP process was done by just monitoring process parameters, such as the induced strain during the lay-up process of glass fiber/high-density polyethylene material [32,114]. A silica optical FBG system [110] was implemented for online monitoring of defects during the TPC AFP. The tested material was thermoplastic glass fiber nylon. First, two plies were placed and consolidated. Then, the optical fiber was placed, see Figure 11a, and aligned on the second ply [110], and seven more plies were placed with a lay-up velocity of 0.01 m/s while the quality was being monitored by the FBG sensors. A reference sample without defects was used to identify phenomena such as resin shrinkage and strain induced by the compaction roller. The reflected wavelength changes during the manufacturing process were measured in order to relate them to the consolidation pressure and curing temperature. Misalignment defects such as Gaps and Overlaps, (see Figure 11b, were detectable through all the seven plies [32,110]. Additionally, the process parameters temperature and strain can be monitored, and structural health monitoring would be possible afterwards, as the optical fibers remain in the part.

A Fiber Bragg grating system allowed online monitoring at a low lay-up velocity of two defects but with little accuracy, as the size and the exact location of the defect was not determined. The low-cost fibers can easily be embedded between the plies without affecting the structural integrity due to their small size [110]. For defect detection in a part with a significantly higher number of plies, more fibers are necessary [114,115].

Figure 11: a) Setup of Fiber Bragg grating sensor for online monitoring b) Reflected wavelength for Gap (between Edge 1 and 2) [110]
**Hybrid system**

A hybrid quality control system combines different technologies of the ones presented before to be able to detect more defect types.

Krombholz [66] described the combination of a forerun, a nip-point and an overrun quality control system. In the forerun, a low-resolution triangulation system detects fiber edges of the adjacent course for path correction. The real-time system consists of a force-torque and a vibration monitoring system within the lay-up head. The overrun system is based on a high-resolution triangulation system (compare to section on 3D Scanning and Table 4). Cemenska [35] delivered an overrun system that combines 3D scanning with the camera of a laser projector for 2D imaging.

While the combination of technologies allowed the detection of more defect types, the total cost for hardware can approach US$ 1,000,000 [30] (see sections on 3D Scanning and 2D imaging).

<table>
<thead>
<tr>
<th>Defect Type</th>
<th>Overrun</th>
<th>Overrun</th>
<th>Overrun</th>
<th>Nip-Point</th>
<th>Inline</th>
<th>Inline</th>
<th>Nip-Point</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ply boundary</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gap</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Overlap</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Twist</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Missing Tow</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dropped Tow</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wrinkled Tow</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bridging Tow</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuzz Ball</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FOD</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Contamination</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tow width</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Splice</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Table 3: Defect detection capabilities by technology*

### 4. CONCLUSION AND OUTLOOK

Automated lay-up machines offer a highly sophisticated manufacturing process for CFRP structures. However, due to the anomalies that can occur during lay-
up, every ply has to be inspected for defects with as little time consumption as possible. Currently, the machines remain idle for more time than they spend laying up, as an inspector performs a visual quality control for which the machine has to be stopped. To reduce the time consumption, but also to increase the reliability, visual quality control by humans needs to be substituted by automated online monitoring. This type of quality control can prevent idle times of the machine, as the quality control takes place while the machine is laying up.

The studied literature reveals that the camera-based technologies 2D imaging, 3D scanning and infrared thermography show promising results concerning the reliability and accuracy of the detection of the different defect types (see Table 4), although they are influenced by the optical reflective properties of CFRP. With such a camera-based online quality control system, the inspection time could almost be reduced completely. The 3D scanning systems are the most developed, partly with visualization and data management features. The automation of quality control will bring additional benefits:

- Detection of defect types that are difficult to detect by humans, e.g. cumulative Gap
- Statistical analysis of the digital records, which can lead to process optimization
- Decreased labor costs by having only one inspector that supervises several AFP machines

<table>
<thead>
<tr>
<th>Defect detection</th>
<th>Time consumption</th>
<th>Interference with lay-up</th>
</tr>
</thead>
<tbody>
<tr>
<td>2D imaging</td>
<td>0</td>
<td>+</td>
</tr>
<tr>
<td>3D scanning</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Infrared thermography</td>
<td>0</td>
<td>+</td>
</tr>
<tr>
<td>Compaction measurement</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>Ultrasonic</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Eddy Current Testing</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>Fiber Bragg grating</td>
<td>-</td>
<td>+</td>
</tr>
</tbody>
</table>

Table 4: Comparison of technologies for online monitoring of AFP
++ very good, + good, 0 ok, – insufficient

Due to their size, the camera-based systems are usually integrated in the overrun, which limits online monitoring of complex parts. While compaction measurement and Fiber Bragg Grating sensors allow the measurement at the nip-point, they show only limited defect detection capabilities.

For the future, the measurement point of the camera-based technologies has to be improved in order for online monitoring to work for complex parts. The challenge is to install the quality control system closer to the nip point in order to check the quality at the placement point and at the same time to not cause
geometrical interference with the lay-up process. This can be accomplished by integrating a line scanner and illumination into a transparent compaction roller [116]. Challenges resulting for the economic point of view can be the costs of such a new quality control system, as extra personnel and training will be needed for the integration into the AFP machine.
<table>
<thead>
<tr>
<th>Type</th>
<th>Technology</th>
<th>Velocity</th>
<th>Resolution</th>
<th>Accuracy</th>
<th>Defects</th>
<th>Material</th>
<th>System*</th>
<th>User interface</th>
<th>Visualization</th>
<th>Data</th>
<th>Usage</th>
</tr>
</thead>
<tbody>
<tr>
<td>[49]</td>
<td>Inline 2D imaging</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>Ply boundary, Gap</td>
<td>N/A</td>
<td>Laser projector and vision system</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>[69]</td>
<td>Inline 3D scanning</td>
<td>2 m/s</td>
<td>N/A</td>
<td>98.4 - 99.7% defect detection</td>
<td>0.142% false positives</td>
<td>N/A</td>
<td>Thermoset</td>
<td>Keyence System Laserguide</td>
<td>N/A</td>
<td>Laser projector, smart watch</td>
<td>N/A</td>
</tr>
<tr>
<td>[62]</td>
<td>Online 3D scanning</td>
<td>1.5 m/s</td>
<td>X: 1.270 mm Y: 0.038 mm Z: 0.003 mm</td>
<td>0.976 mm 1.22 mm</td>
<td>Ply boundary, FOD, BOD</td>
<td>Thermoset</td>
<td>5.98 mm laser width 7-12 aBUS 20.000</td>
<td>N/A</td>
<td>Laser projector, Part number, date, ply, course, etc.</td>
<td>N/A</td>
<td>In 2017 4 automated inspection systems were in use in production for commercial aircraft</td>
</tr>
<tr>
<td>Party online 2D imaging</td>
<td>0.1 m/s</td>
<td>Y: 0.076 mm Z: 0.127 mm</td>
<td>N/A</td>
<td>N/A</td>
<td>Thermoset</td>
<td>Stendalab 1-Scan laser line scanner and T-Track optical scanning system 100mm long laser line</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>Earlier work was done with F/WES and now with Automated Dynamics</td>
<td></td>
</tr>
<tr>
<td>Online 3D scanning</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>Thermoset</td>
<td>Epoxy</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>Online 3D scanning</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>Fibre connection</td>
<td>Epoxy</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>Online 3D scanning</td>
<td>1 m/s</td>
<td>Position of defects</td>
<td>N/A</td>
<td>N/A</td>
<td>Thermoset</td>
<td>Epoxy</td>
<td>Measurement 100mm ballpen compaction roller</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>Qualification with Mitsubishi and Airbus Planned for A350 production</td>
</tr>
<tr>
<td>Online Infrared Thermography</td>
<td>0.23 m/s</td>
<td>Y:0.23 mm</td>
<td>N/A</td>
<td>N/A</td>
<td>Thermoset</td>
<td>Epoxy</td>
<td>AT camera 150 mm sharp area 950 x 950 pixels</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>No sound Compaction measurement</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>Thermoset</td>
<td>Epoxy</td>
<td>Eddycurrent, MPECS by Suruga</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>Online Fiber Bragg Grating</td>
<td>0.01 m/s</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>Thermoset</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
</tr>
</tbody>
</table>
5. **GLOSSARY**

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>AFP</td>
<td>Automated Fiber Placement</td>
</tr>
<tr>
<td>ATL</td>
<td>Automated Tape Laying</td>
</tr>
<tr>
<td>CFRP</td>
<td>Carbon Fiber Reinforced Polymers</td>
</tr>
<tr>
<td>course</td>
<td>a single pass of up to 32 tows</td>
</tr>
<tr>
<td>DFP</td>
<td>Dry Fiber Placement</td>
</tr>
<tr>
<td>EOP</td>
<td>Edge of Ply</td>
</tr>
<tr>
<td>FOD</td>
<td>Foreign Object Debris</td>
</tr>
<tr>
<td>NDI</td>
<td>Nondestructive Inspection</td>
</tr>
<tr>
<td>TPC AFP</td>
<td>Thermoplastic Composite Automated Fiber Placement</td>
</tr>
<tr>
<td>floor-to-floor time</td>
<td>the total time the tooling is located in the AFP cell</td>
</tr>
<tr>
<td>inline quality control</td>
<td>inspection of the quality after a ply is finished</td>
</tr>
<tr>
<td>inspection</td>
<td>quality control as an ad hoc step</td>
</tr>
<tr>
<td>inspector</td>
<td>the person who is in charge of the final inspection of a ply</td>
</tr>
<tr>
<td>machine run time</td>
<td>the time during which the machine is laying up</td>
</tr>
<tr>
<td>monitoring</td>
<td>quality control continuously performed</td>
</tr>
<tr>
<td>operator</td>
<td>the person who is charge of the lay-up machine</td>
</tr>
<tr>
<td>online quality control</td>
<td>monitoring of the quality while the machine is laying up</td>
</tr>
<tr>
<td>ply</td>
<td>a fully covered area with tows in one direction</td>
</tr>
<tr>
<td>rework</td>
<td>the act of removing a defect during the lay-up process</td>
</tr>
<tr>
<td>repair</td>
<td>the act of removing defects after the part is cured</td>
</tr>
<tr>
<td>Splice</td>
<td>overlapping joining of two tow ends to Splice</td>
</tr>
<tr>
<td>tow</td>
<td>a single strip of carbon fiber</td>
</tr>
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6. LITERATURE

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