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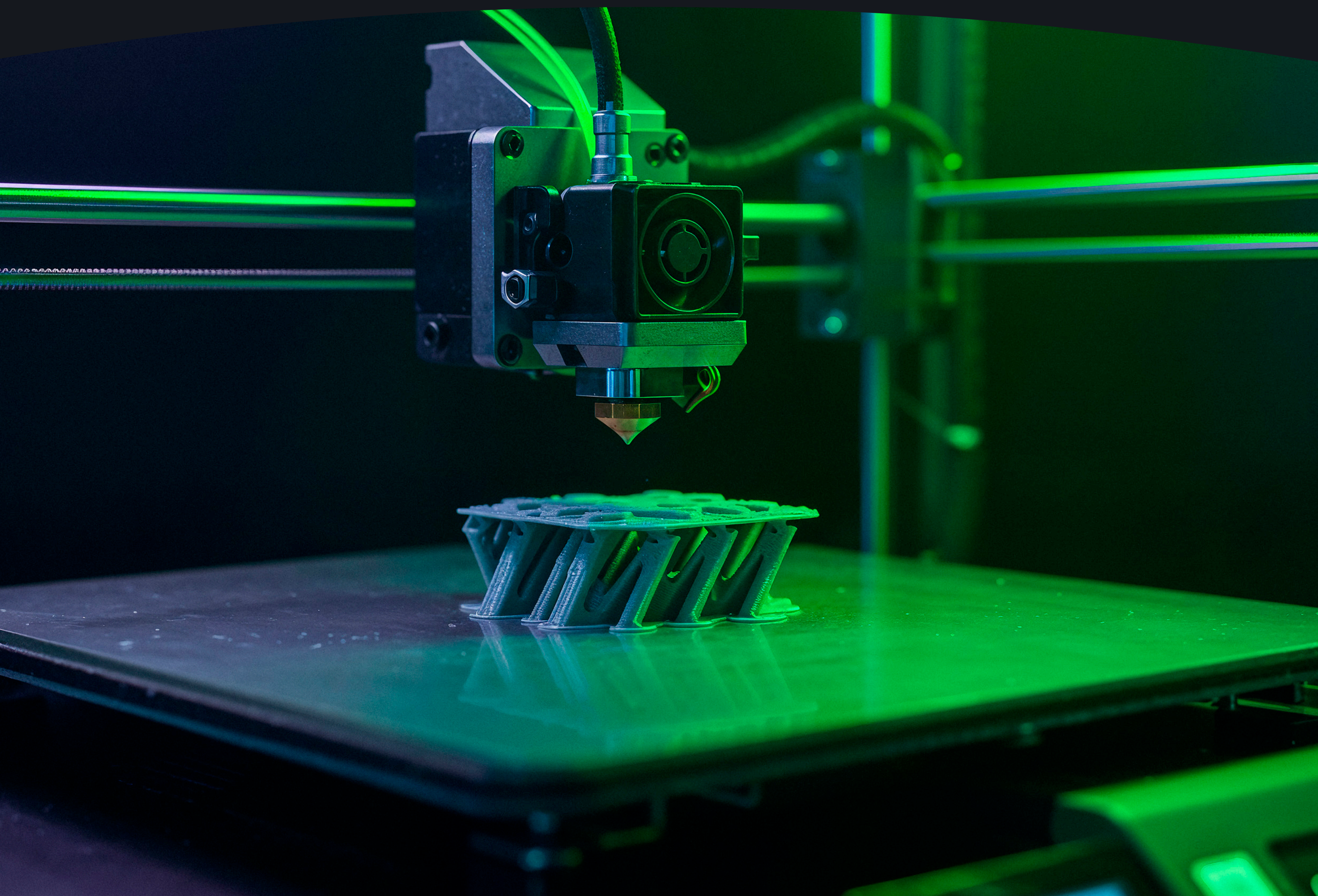
PRIMER

Additive Manufacturing of Conventional Military Equipment: Implications for Arms Control and Security

SARAH GRAND-CLÉMENT • SUNNIVA SELMER REINERTSEN



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About UNIDIR

The United Nations Institute for Disarmament Research (UNIDIR) is a voluntarily funded, autonomous institute within the United Nations. One of the few policy institutes worldwide focusing on disarmament, UNIDIR generates knowledge and promotes dialogue and action on disarmament and security. It is based in Geneva and assists the international community in developing the practical, innovative ideas needed to find solutions to critical security problems.

Notes

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Acronyms and abbreviations

AI	Artificial intelligence
AM	Additive manufacturing
ATT	Arms Trade Treaty
CAD	Computer-assisted design
CNC	Computer numerical control
OEM	Original equipment manufacturer
IP	Intellectual property
ITT	Intangible technology transfer
MTCR	Missile Technology Control Regime
POA	United Nations Programme of Action to Prevent, Combat and Eradicate the Illicit Trade in Small Arms and Light Weapons in All Its Aspects
UAV	Uncrewed aerial vehicle
UNROCA	United Nations Register of Conventional Arms
WA	Wassenaar Arrangement on Export Controls for Conventional Arms and Dual-Use Goods and Technologies
WMD	Weapons of mass destruction

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Executive summary

Additive manufacturing (AM), also known as 3D printing, is increasingly being adopted in defence and military contexts, with significant implications for conventional arms production, arms control and international security. While AM is not a new technology, recent advances in machine capabilities and declining costs have accelerated its integration into military supply chains, operational environments and industrial production. As a dual-use, cyber-physical manufacturing technology, AM offers strategic advantages, but it also raises proliferation and diversion risks that warrant closer scrutiny by policymakers and the arms control community.

AM is currently used primarily to manufacture military parts and components, rather than complete weapon systems. These military parts and components have a range of uses in crewed and uncrewed systems in the air, land and maritime domains. AM has seen particular applications in aerial systems, such as the manufacturing of structural components as well as engines. Militaries employ AM to rapidly prototype tools, repair or replace obsolete or unavailable components, and produce lightweight or highly customized parts with complex geometries. These capabilities can enhance operational readiness, resilience and sustainment by reducing dependence on vulnerable or slow traditional supply chains.

Despite its technical promise, AM faces drawbacks and limitations that restrict its wider application. Key limitations include difficulties in standardization and certification, variability in output quality, intellectual property barriers, shortages of skilled personnel for advanced AM applications, and poor scalability for mass production. As a result, there remains a notable gap between what AM can technically produce and how widely it is actually used for mission-critical military applications.

Nonetheless, the growing diffusion of AM introduces a range of diversion and proliferation risks. These risks depend on factors such as the type of AM technology, the outputs produced and what capabilities these enable. The diversion and proliferation risks can manifest themselves via access to physical machines and feedstock, digital design files and software, and via the expanding group of actors involved, many of which are outside traditional defence-industrial bases. Digital AM files and associated know-how are particularly difficult to control, given the ease with which intangible technology can be shared.

Implications of these risks include greater access to controlled capabilities, which has the potential to erode the effectiveness of export control and sanctions regimes that are primarily designed around physical goods and international transfers. The decentralization of production and reduced reliance on cross-border supply chains may also undermine transparency and confidence-building mechanisms that focus on national production and procurement reporting.

Existing multilateral control frameworks partially address AM. Export control regimes such as the Wassenaar Arrangement, the Missile Technology Control Regime (MTCR), and the European Union's Dual-Use Regulation control certain high-end AM machines, materials and related technologies, including intangible technology transfers (ITTs). However, controls remain uneven and guidance on ITTs can lack clarity and uniformity. Other instruments, such as the Arms Trade Treaty (ATT) and the United Nations Programme of Action on Small Arms and Light Weapons, address aspects of arms transfers and production but do not fully capture the unique challenges posed by AM.

As AM continues to diffuse across military and civilian sectors, governance approaches must evolve accordingly. Policymakers could consider the following non-exhaustive avenues for action:

- **Strengthening the application of multilateral control measures:** This category of actions relates to elements that can strengthen the application of multilateral control measures. Avenues include using the ATT framework to examine regulation of (intangible) transfers that assist the AM of conventional arms; the establishment of international standards and their use to complement and reinforce regulatory measures; the development and implementation of practical and harmonized approaches to ITT regulation; the exploration of technological solutions to identify diversion and proliferation risks; and the stemming of the erosion of transparency and confidence-building by reporting on national production using AM.
- **Addressing gaps, limitations and challenges of national export control mechanisms:** Avenues to address gaps, limitations and challenges in national export control mechanisms include the development of capacities to detect, prosecute and enforce regulations of tangible and intangible AM technology; and the development of risk profiles to better understand and address AM risks.
- **Raising-awareness and improving industry compliance:** Industry responsibility plays an important role in mitigating risks from AM, and notably from ITTs. This can be boosted by raising awareness and building capacity of actors involved in AM; by implementing adequate industry due diligence in order to prevent and mitigate risks posed by AM technology; and by ensuring the traceability of AM supply chains.

3D printed bomb for aerial drone made by Ukrainian army specialists, Kyiv, 2024. Credit: hurricanehank / Shutterstock.

1. Introduction

Reports on the uses of additive manufacturing (AM) for military applications demonstrate its growing relevance for military uses. These uses range from printing turbojet engines for uncrewed aerial vehicles (UAVs)[1] to the use of mobile AM facilities by deployed troops.[2] However, AM technology – which encompasses the machines, associated material and the digital data, which can be used for both civil and military purposes – can pose diversion and proliferation risks. The level and type of risk varies, depending on factors such as the type of AM technology, the outputs produced and what capabilities these enable. The risk also depends on the extent to which AM technology confers manufacturing capabilities that challenge the state monopoly on the use of force, enhances warfighting ability to the detriment of civilian populations and infrastructure, or enables destabilizing accumulations of conventional arms. As a result, AM requires closer understanding and scrutiny by the arms control and disarmament community.

Additive manufacturing, also known as 3D printing, refers to a process that forms, or prints, a three-dimensional object layer by layer, based on a digital file. AM is an umbrella term that encompasses different types of techniques. Unlike other manufacturing techniques, which are limited by the manufacturing process itself, AM aims to enable design and manufacture according to the intended function of the output, rather than according to limitations driven by the manufacturing process itself.[3]

AM is not a new technology; the first type of AM machine was patented in the 1980s.[4] Three main factors have brought AM into the manufacturing mainstream: the expiry of initial patents, which allowed broader commercialization of certain types of AM printer;[5] technological improvements; and decreased costs. As a result, interest in and use of AM has grown in various industrial sectors (e.g., the medical, automotive, maritime and aerospace sectors), as well as for individual use – including illicit applications (see Box 1).

The defence sector is one of the areas where there has been a notable and long-standing interest in AM technology because of:

- Cost considerations
- Fast production of spare parts during a mission
- Fragility of supply chains in traditional manufacturing
- The current rise in conflicts worldwide and related increased focus on military equipment production, sustainment and maintenance

This is reflected in recent government strategies and actions that foresee increased use of AM in defence production and military contexts,[6] while also creating the infrastructure to facilitate military AM use.[7]

BOX 1.

Illicit use of additive manufacturing

While this primer focuses on the use of additive manufacturing as a production technology by state actors, AM is also being used for illicit purposes by non-state armed groups (NSAGs), terrorist organizations and organized criminal groups.[8] These entities notably use AM to illicitly manufacture weapons and their parts and components, such as small arms and light weapons (SALW) and UAVs.[9]

This is not a new trend: AM designs for both AM weapon components and firearms have existed since the early 2000s.[10] In 2013, the computer-assisted design (CAD) files of the first functioning fully 3D-printed gun was released online for free public download.[11] While initially dismissed as rudimentary, designs of AM weapons have steadily improved, resulting in sophisticated, durable and lethal weapons[12] that have been used for crimes and acts of terrorism.[13] However, these weapons are still generally less functional and durable than their traditionally manufactured counterparts, with a higher vulnerability to defects.[14]

Illicit use of AM has also been confirmed in multiple conflict zones.[15] For example, a 2026 UNIDIR report documents the use of AM by NSAGs in Myanmar, noting that AM "has become a key enabler for the production not only of small arms and munitions, but also of some structural [UAV] components".[16]

This primer is based on three information sources:

- A review of the relevant literature
- A series of interviews held between November 2025 and February 2026 with 13 experts from academia, applied research, industry and arms control (see Annex I)
- Insights shared during a multi-stakeholder dialogue organized by UNIDIR in February 2026[17]

This primer is intended for diplomats and policymakers working on questions of conventional arms and transfer control. Additional relevant stakeholders include the private sector, civil society and others involved in questions relating to evolution in manufacturing and related international security concerns.

The primer is structured as follows. Section 2 starts by providing a short overview of what AM is and how it works. Section 3 explains what types of military equipment AM can help produce, who is involved, why it is sought and what are its limitations. Section 4 then examines the risks emerging from AM as a production technology, while Section 5 provides an overview of existing arms control and transfer control measures and their gaps and limitations. Section 6 concludes by providing several considerations for policymakers on how to overcome existing challenges.

2. How additive manufacturing works: process and techniques

This section first provides a brief explanation of how additive manufacturing works and how it differs from other manufacturing processes, before giving an overview of the different AM techniques.

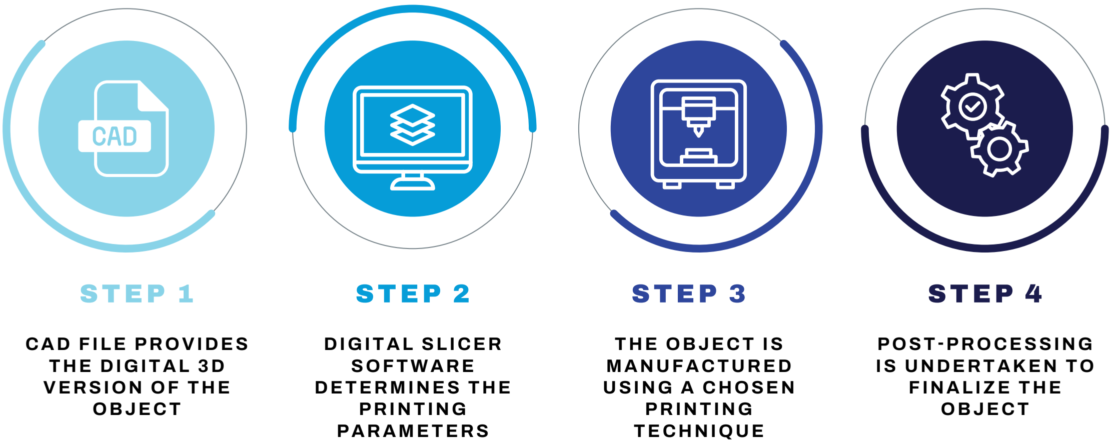
2.1. The additive manufacturing process

AM involves physical and digital components, including a printer, feedstock (i.e., the raw material used to manufacture outputs) and digital files. Broadly, a digital file is created and processed to enable the production of a physical output, followed by post-processing. The four steps are summarized below and visualized in Figure 1 (although details differ slightly between AM techniques).[18]

1. A digital file of the object to be created is required in the form of a CAD file. A CAD file involves the creation and modelling of a digital 3D design of an item and contains other data on the item. This design stage is critical and requires specific know-how, particularly in terms of adapting and improving the design.
2. Digital slicer software is used to determine the layers of the part to be made – in other words, it breaks down the object into slices for the machine to build, layer by layer. Beyond defining the layers, this step also provides specific instructions within the file for how the machine should manufacture the output. This includes, for example, specifying how much material should be deposited at specific points, the movement of the laser or extruder, as well as the machine settings (e.g., temperature, speed, or the location and quantity of supports). This overall set of parameters has a direct impact on the quality of the part produced.
3. An AM machine creates the part based on this digital data (further discussed in Section 2.2).
4. Finally, post-processing is applied to the printed object. This may include cleaning the object (e.g., removing any supports that were used in the printing), heat treatment, machining, polishing and coating[19] to ensure that the object is of the necessary quality. After the manufacturing process itself, inspection and quality control may also occur to check the integrity and usability of the object.

FIGURE 1.

Overview of the key steps in the additive manufacturing process



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As a manufacturing technique that "prints" an output from scratch, AM is the opposite of what is referred to as subtractive manufacturing, whereby a block of material is carved or shaved down to form the output. AM also differs from manufacturing techniques where material is formed into shape through either heating or pressure (e.g., casting, moulding and forging). These other manufacturing techniques rely on pre-made shapes from which parts are made, which can introduce design constraints.

A 3D printer prints the base of a design out of filament at the Viper Innovation Cell at Shaw Air Force Base, 2023. Credit: U.S. Air Force photo by Senior Airman Kevin Dunkleberger.

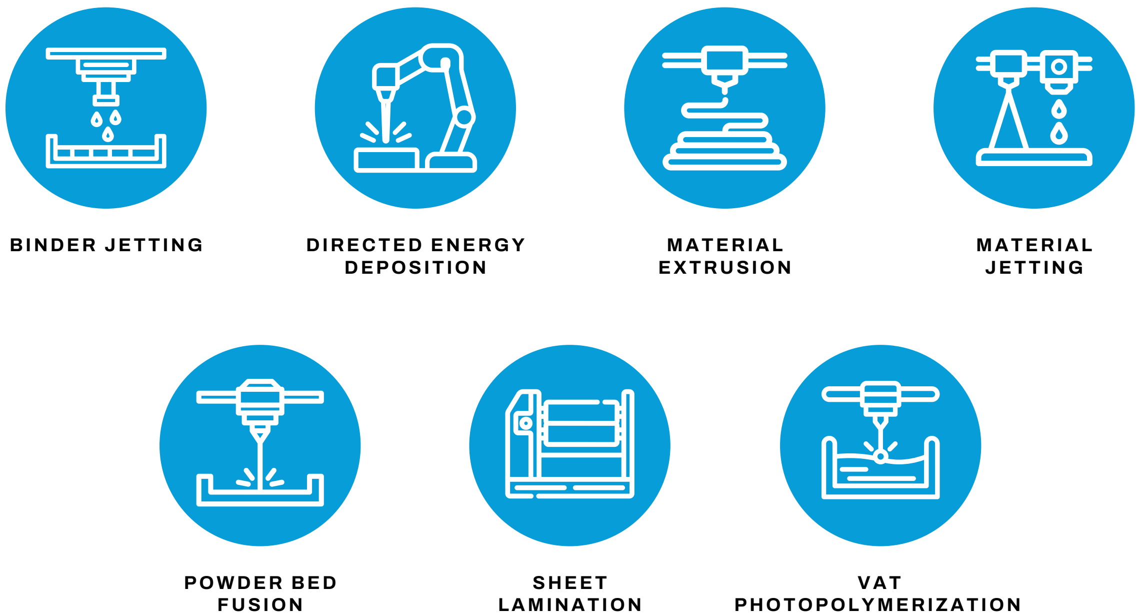
Because AM relies on digital files and software to produce parts and components, it is also referred to as a cyber-physical manufacturing technique. AM shares similarities with other cyber-physical manufacturing techniques, such as computer numerical control (CNC) machining – a subtractive machining technique that also uses CAD files whose code controls the gradual and precise turning, carving or milling of a single piece of material.[20] Despite the similarities, AM and CNC machining offer different opportunities (see Section 3). Nonetheless, they can complement each other, such as through hybrid AM, in which AM and CNC machines are used as an integrated unit, each addressing the other's limitations[21] while reducing costs.[22]

2.2. Additive manufacturing techniques

The ISO/ASTM 52900 standard defines seven overarching AM techniques, visualized in Figure 2.[23] Each of these techniques includes further subtypes. For example, a well-known subtype of the material-extrusion technique is fused deposition modelling (FDM), which is commonly used in commercially available AM machines.[24]

FIGURE 2.

Key techniques of additive manufacturing



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Different AM techniques use different types and forms of feedstock. The range of feedstocks that can be used in AM include commercial and higher-end, specialized metals and alloys, polymers and ceramics. Feedstock can come in various forms, such as liquid, filament, powder and sheets of material, depending on the technique used.

The type of output to be produced will ultimately dictate the selection of the AM technique. Innovations are also continuously being made, expanding what is possible to produce, in terms of the quality and the properties of the output (see Box 2).

BOX 2.

Expected future developments in additive manufacturing

Advances in additive manufacturing are expected to expand the use and spread of the technology. Three of these future developments are outlined below:

1. **Significant research and development investment is focused on improving and developing new materials for AM.**[25] This includes developing 4D printing, which uses smart materials that can change their properties when in contact with external stimuli, including temperature, pressure, light or magnetic fields.[26]
2. **Developments are continuously made to AM hardware.** Machines are being adapted to accommodate newly developed and improved materials and their changed material properties.[27] There is also increasing demand for faster and more efficient printers, reflected in continuous improvements in speed, size and precision.[28]
3. **Artificial intelligence (AI) is also expected to play a greater role in AM,** with the potential to be employed at all stages of the AM process. AI could enhance the design phase through generative design[29] and could reduce errors by running simulations of design performance prior to producing any output.[30] The workflow may also be sped up and improved as it relates to testing material efficiency and structural integrity.[31] AI can also support the certification of outputs through AI-powered monitoring systems[32] and the creation of digital twins (in which an otherwise undetectable defect can be spotted).[33]

World-leading 3D printer used by the British Army in the field for first time, 2024. Credit: UK MOD, Crown.

3. Application of additive manufacturing in the defence context

This section provides an overview of the types of outputs that can be produced using additive manufacturing (in Subsection 3.1), outlines the actors involved in the development and use of this technology (in Subsection 3.2), and explains why AM is sought in defence contexts as well as what hampers its broader use (in Subsection 3.3). It then (in Subsection 3.4) highlights the main takeaways regarding the application of additive manufacturing in the defence context.

3.1. Production of conventional weapons via additive manufacturing

AM is not yet used to manufacture entire weapon systems. To-date, it has mainly been applied to manufacture a range of military parts and components.[34] A non-exhaustive overview of specific types of military equipment produced using AM follows. Although information on each of these AM outputs is available in the public domain, the available information is limited.

Land systems (including uncrewed ground vehicles)

Use of AM in land systems to date has reportedly focused on parts and components for repairing tanks (e.g., mounts, connectors and hulls).[35]

Maritime platforms (including uncrewed maritime vehicles)

AM has been used in maritime platforms for manufacturing parts and components (e.g., valve manifold assemblies) for submarines, other underwater equipment[36] and other maritime platforms.[37] For example, AM has been used to manufacture the propeller of a minehunter.[38]

AM has also been used to manufacture parts and components of uncrewed maritime vehicles, including their hulls.[39]

Aircraft (including uncrewed aerial vehicles)

AM components used in aerial systems include brackets[40] and fuel nozzles.[41] Some references to outputs are less specific, for example, only mentioning the use of AM for "flight-critical parts"[42] or "large-scale airframe parts",[43] including cockpit parts for stealth aircraft.[44] AM has also been used to produce rotor systems for attack helicopters.[45] With regards to UAVs, AM can be used to reduce the weight of structural components of UAVs while maintaining strength. Thus, AM components of UAVs include airframes, payload mounts, canopies and propellers.[46] AM can also be used to manufacture entire UAVs, with their sophistication ranging from low-end, commercial-grade machines[47] to higher-end systems.[48]

Missiles

While the example of Raytheon manufacturing 80 per cent of a guided missile using AM is often cited,[49] most missile-related outputs appear to be parts and components (e.g., fins and guidance systems).[50] These AM parts and components overlap with those produced for aircraft (e.g., engine components; see below). Other AM use relates to the creation of small pyrotechnic devices.[51]

Engines

AM has been used to manufacture engines and their components (e.g., turbine blades, combustion chambers, engine nozzles), including for UAVs,[52] missiles[53] and rockets.[54]

SALW and artillery systems

Beyond its illicit use (as discussed in Box 1), AM has also been used in industrial production of SALW and artillery systems. This includes AM use for prototyping,[55] the manufacturing of suppressors[56] and of unspecified components for artillery systems.[57]

Energetics

With regards to energetics, AM can be used to manufacture a range of propellants,[58] with uses ranging from rocket engines[59] to SALW.[60] The use of AM for manufacturing explosives is of particular interest due to its ability to create "complex internal lattices and structures that influence the explosive characteristics of each build."[61] In other words, AM offers the opportunity to create more effective explosives while also enabling more control over the direction of an explosion via the structure of the AM object.[62] This allows specific effects, including minimization of collateral or environmental damage, to be achieved.[63] AM can also be used to manufacture artillery shells or casings[64] as well as grenades.[65]

Electronics

AM can be used to manufacture certain electronic components such as antennas, waveguides (a component used in radars), radiofrequency filters (a component used to protect equipment from electromagnetic interference)[66] and related electronic technologies.[67] AM also enables integrated circuits and sensors to be directly embedded in AM-manufactured parts.[68]

3.2. Actors involved in additive manufacturing

There are a growing number of producers and actors involved in AM, including actors that have not traditionally been part of the defence sector, which may usher in specific risks (see Section 4). The breadth of actors and their various roles in the AM space includes the following.

Producers of AM machines and associated material

These include both companies that produce commercial AM machines and those that produce high-end, specialized AM machines, as well as companies providing feedstock and other material required for AM.

Commercial actors producing AM outputs

Among these actors are companies in the defence-industrial base that are involved in the delivery of military systems and their components and subcomponents for defence ministries. This includes major defence companies and original equipment manufacturers (OEMs). It also includes companies that originally produced commercial items but have pivoted to also manufacture outputs intended for military use, as well as print-on-demand businesses that manufacture items based on digital files that are shared with them. In some instances, commercial actors producing AM outputs can also be producers of AM machines and associated material.

Militaries

While military personnel are usually the users of complete conventional arms systems, they are now also using AM machines to manufacture parts and components directly, either in military bases, on vessels or in the field, including on the front lines via mobile AM solutions.

Research and academic institutions

These entities notably help advance research on, and applications of, printing techniques and new materials. These can be, but are not always, affiliated with a government or the defence-industrial base.

3.3. Current purposes and limitations of additive manufacturing technology in the defence sector

3.3.1. Purposes

There are three key purposes for which AM is used in the defence sector and the manufacturing of military equipment.

First, is its ability to **rapidly produce tooling and prototypes**. AM can produce tools and prototypes more easily and faster than traditional manufacturing processes.[69]

Second, AM can aid with **rapid and mobile production of parts and components**. This enables sustainment, repair and obsolescence management, and thus greater operational readiness and resilience.[70] For example, AM can be used in cases where replacement parts are no longer available or the original manufacturer no longer exists.[71] In the context of a military operation, the ability to ensure usability of equipment and overall sustainability of operations can be key factors in success. AM can also help manage the costs and timeframe associated with the sustainment and repair of military equipment, both during and beyond military operations.[72]

As such, AM reduces reliance on the traditional supply chains set-up, although it neither eliminates supply chains nor entirely removes reliance.[73] For example, AM can be undertaken in mobile platforms, thus enabling remote and or in-field manufacturing.[74] This can reduce the time between identifying a need and obtaining the item. Interviewees have described how this timeline can be reduced from as much as months to as little as days when using AM in place of other manufacturing processes.[75]

Third, AM can **create outputs with more complex or novel properties** than traditional manufacturing processes.[76] AM can be more precise, can enable greater customization of outputs, and can produce shapes and structures (e.g., hollow parts) unconstrained by the limits imposed via traditional manufacturing process.[77] What this means in practice is the ability to produce more lightweight parts[78] and to overcome the need to join separate parts together, instead manufacturing an object as a whole. [79] These properties are of particular interest in the aerospace domain, which continually seeks to optimize the size, weight and power of aerial systems.[80]

3.3.2. Limitations

Despite offering a range of opportunities, AM also faces a series of limitations that can hamper its wider application.

First, **intellectual property (IP) and other legal considerations hinder both interoperability and repairability of AM outputs**. With the growth of in-house production capabilities, some OEMs may be hesitant to share their digital design files given the associated lack of control of outputs.[81] In addition, whether a manufacturer has the "right to repair" (i.e., the legal ability to conduct in-house disassembly, repair and reassembly of a broken part) will be specified in the purchasing contract and varies greatly according to the part in question.[82]

Second, **standardization and certification of parts is challenged by the variability of AM outputs**. In traditional manufacturing, repeated production of an object results in an understanding of its strength and fatigue behaviour. With AM, in contrast, differences emerge according to changes in machine, feedstock and process, with metal AM outputs being particularly vulnerable to variability.[83] This causes a higher chance of hard-to-detect defects, in addition to a lack of standardization of outputs.[84] This thus limits the use of AM outputs by military and other critical industries as outputs may not meet the necessary trust level for use.[85]

Third, **there is a skill gap for higher-end AM**. AM requires experienced and skilled machinists to produce more sophisticated AM designs, with the know-how to fine-tune parameters, design solid structures, and inspect and finish the output.[86] Higher-end AM is thus hampered by the lack of in-house designers with these required skills.[87]

Fourth, **AM is not suited for scalability and mass production**. Its significant reliance on skilled or semi-skilled labour increases production expenses,[88] while its speed remains slower than many traditional production methods, such as casting.[89] Transitioning from its current primary use as a prototyping tool to higher-volume production is therefore a challenge.[90]

3.4. Contextualizing additive manufacturing in the defence context

Several overarching points emerge regarding the use of AM for military and defence purposes.

First, there is a **notable difference between what is technically feasible versus how AM is actually used**. The information in the public domain primarily outlines what AM can produce, but does not provide data on the extent of actual use. The limitations of AM use – that is, on the application of standards and certification – highlight potential reticence to use AM outputs or constrains their use. Considerations of cost or the ability to mass produce can also have an impact on the decision to use AM over other manufacturing techniques.[91]

As such, access to machines, associated materials or the digital files does not automatically imply that AM will or can be used, or that it would be usable to manufacture military equipment or its parts and components. There are many factors beyond the hardware and software that affect decisions to use AM, such as the ability to create or adapt a 3D design, adequate equipment for post-processing, and the ability to verify the viability of the outputs.

Second, **the intended output can influence the decision to use AM**. There may be different levels of willingness to use AM depending on risk perceptions related to manufacturing (e.g., energetics) and use risks. For example, while there may be less willingness to use AM for critical components in crewed platforms,[92] the risk calculus can be different when it comes to uncrewed systems. Notably, the United States Department of Defense has recently relaxed requirements for additively manufactured UAV components,[93] while the Indian Armed Forces is also exploring the use of AM for UAVs.[94]

Third, **circumstances of use can affect the level of acceptability around adoption and use**. Wartime conditions can increase the acceptability of the technique in relation to some of its drawbacks.[95] In the case of the war in Ukraine, for example, AM machines have been employed as part of the equipment-sustainment effort. This has included manufacturing parts for ammunition or bomb casings, UAV parts, as well as parts for repair.

3D printing aboard USS Essex (LHD 2) during Noble Fusion, 2022. Credit: U.S. Marine Corps / Sgt. Israel Chincio.

4. Additive manufacturing risks and their implications

This section examines the risks associated with the different aspects of the AM production cycle. Specifically, **AM technology can raise risks of diversion and of proliferation**. These risks – which differ depending on the regulatory measures that are in place, the output type and the intention of the end user – can manifest themselves via the physical material (see Subsection 4.1), digital data (see Subsection 4.2) or actors (see Subsection 4.3) involved in AM. The section closes (in Subsection 4.4) by outlining the implications of these risks.[96]

4.1. Machines and associated physical material

AM machines and associated physical material (e.g., feedstock) form the tangible elements enabling AM. Risks include the diversion of these elements from their legal end use or end user either at point of purchase, during their transfer or at point of use (e.g., during deployment and in-field operations by military actors). Proliferation risks are associated with the use of AM machines and associated material, including commercial AM machines or materials, to produce weapons or their parts and components.

The level and type of risk varies, depending on the type of AM technique and the material used. Some techniques (e.g., powder bed fusion) have greater applicability in the defence sector due to their ability to produce complex, strong and durable parts.[97] Similarly, risks related to associated physical material also differ. For example, level of risk varies according to the varying quality and grade of feedstock: polylactic acid, a widespread type of polymer for AM, would be used for very different applications than a military-grade metal such as maraging steel.

AM machines are also vulnerable to cyber interference.[98] A malicious actor may target AM machines to affect their functionality or to steal data processed on the machines, generating both operational and diversion risks. The vulnerability of AM machines stems in part from their Internet connectivity. Even when machines are disconnected from the Internet as a security precaution, they may still be vulnerable when installing an update.[99]

4.2. Transfers of intangible technology and knowledge

Digital files, which are considered intangible technology, can be at risk of diversion, but can also easily proliferate due to their digital nature. Indeed, **intangible technology transfers (ITTs) of digital AM files poses a key risk.**[100] Intangible technology, as defined by the Wassenaar Arrangement on Export Controls for Conventional Arms and Dual-Use Goods and Technologies (WA), includes both “technical data” and “technical assistance”.[101] According to the WA, “technical data” includes the blueprints or digital files that have the information on how a machine should manufacture an item, including all the machine and build parameters; AM “technical assistance” covers the skills and know-how required to manufacture outputs using AM, which can be transferred through instruction, training or consulting services.

AM (like other manufacturing capacities) may also become an attack surface that adversaries might target in a conflict situation. This could take the form of malicious modifications to design files or their parameters to affect the final output.[102] Such a defect would be designed to go unnoticed by the operator but could cause the part to fail during use.[103]

The key role of digital AM files, combined with the ease with which digital files can be shared (e.g., via email) underscores how ITT challenges extend to AM technology. Controlling ITTs is an ongoing challenge for state actors (see Section 5). This issue is exemplified by a recent enforcement case in which an AM company was found to have undertaken unauthorized exports and re-exports of technical data to several countries and individuals.[104]

However, the risks of the intangible technology should not be generalized. Data from digital files, skills and know-how do not all carry the same levels of risk. For example, data on non-critical parts are not subject to export controls, whereas data on controlled items entails a different level of risk.

4.3. Actors

Actors involved in AM (outlined in Subsection 3.2) can contribute to the risks posed by AM by – knowingly or unknowingly – not abiding by export rules and regulations as well as by introducing supply chain security risks.[105] Certain actors may not be aware of the expectations when producing and exporting both tangible and intangible military or dual-use goods. For example, commercial actors, including print-on-demand businesses, may unknowingly manufacture outputs intended for military use and may be unaware of the risk assessments or due diligence required for such outputs. This can include inconspicuous issue areas, especially regarding intangible technology, such as server location or whether digital AM files are saved on the cloud.[106]

Another challenge relates to the conduct of adequate due diligence (e.g., applying the “know your customer” or subcontractor principles), and thus the ability to ensure that subcontracted companies (and any of their own suppliers) will adhere to rules and regulations that apply to military or dual-use technology.[107] Fragmentation in supply chains can reduce oversight – in terms of who has access to what data; over who manufactures what, and to what extent; as well as what items are manufactured – providing a possible pathway to non-compliance with existing regulations, in addition to proliferation risks.

4.4. Implications emerging from the risks posed by AM

The diversion and proliferation risks associated with AM technology therefore stem from various elements. Among these are its dual-use nature, its cyber-physical characteristics and its ability to circumvent established supply chain dynamics. The implications of these risks are outlined below.

4.4.1. Maintaining or accessing advanced conventional weapon capabilities

AM may increase access to technologically advanced conventional weapons (e.g. missiles), which have traditionally been subject to stricter controls than traditional infantry materiel, for example.[108] Additionally, AM makes it easier to modify the original properties of items. For example, a non-controlled item could be enhanced or otherwise modified with the help of AM technology (either physical or digital), such as by adding functionalities or novel capabilities.[109] While this implication comes with a number of caveats (described in Section 3), it can nonetheless entail that warfighting capability is sustained, if not improved.

4.4.2. Erosion of export control systems and sanctions regimes

Current export control regimes are predicated on the ability of states to regulate international transfers of conventional weapons and controlled items and ensure adequate controls to prevent destabilizing proliferation, particularly with regard to tangible goods. The digital element of AM can therefore undermine the existing systems, in addition to AM's ability to reduce reliance on international supply chains and decentralize production, which can hinder traceability.[110] Therefore, illicit access to AM machines, and their potential use to manufacture controlled items through the illegal transfer of sanctioned technology, could enable states and other entities to circumvent United Nations sanctions by locally producing sanctioned goods using AM machines or by using AM service providers. This could be avoided if sanctions regimes were to include provisions on AM and appropriate enforcement.[111]

4.4.3. Undermining transparency and confidence-building mechanisms

Arms control transparency and confidence-building measures, such as the United Nations Register of Conventional Arms (UNROCA), have focused on the sharing of information on international transfers and on procurement through national production of complete conventional weapon systems. However, few states report on procurement through national production, which is a data gap that could be exacerbated should AM use continue to expand.

5. Existing multilateral control measures for additive manufacturing

This section first outlines the existing arms and transfer control measures, including whether and how AM is encompassed within them (in Subsection 5.1). It then describes (in Subsection 5.2) the existing challenges and gaps in the control measures.

5.1. Arms and transfer control measures

Existing multilateral measures seek to regulate and prevent the illicit arms trade and to apply export controls to prevent diversion and uncontrolled proliferation.[112] This subsection explores how AM is being considered by these measures by first examining how two multilateral control regimes and one regional export control regulation – the Wassenaar Arrangement, the Missile Technology Control Regime (MTCR), and the European Union's Dual-Use Regulation – seek to address controls on AM via their control lists.[113] It then examines the role of two other instruments – the Arms Trade Treaty (ATT) and the United Nations Programme of Action to Prevent, Combat and Eradicate the Illicit Trade in Small Arms and Light Weapons in All Its Aspects (PoA).

The **Wassenaar Arrangement**, which has 42 participating states, promotes "transparency and greater responsibility in transfers of conventional arms and dual-use goods and technologies".[114] Its control list, which is reviewed and updated annually, includes certain AM machines or their component lasers, other AM equipment, and metal powders (which act as feedstock).[115] Beyond the specific elements explicitly mentioned in the control list, the WA has a "catch-all" measure. This measure enables states to conduct controls on dual-use items that do not appear in the control list, but which could be used to produce or proliferate weapons of mass destruction (WMD) or military equipment in countries subject to a United Nations Security Council arms embargo.[116]

The participating states of the WA have also developed guidance on intangible technology transfers related to tangible items included in the control list and best practices on the implementation of controls on ITTs. Among these best practices are that national laws and regulations should clearly define ITTs; states should specify in their laws or regulations which ITTs are subject to export control; and states should promote awareness-raising on ITT controls among relevant stakeholders, such as industry and academia.[117]

The **Missile Technology Control Regime**, which has 35 partner states, aims to "coordinate national export licensing efforts aimed at preventing proliferation of unmanned delivery systems capable of delivering weapons of mass destruction",[118] which includes UAVs. The MTCR control list, called the Annex, does not explicitly mention or include AM.[119] It does, however, include references to "specially designed" production equipment and materials used to manufacture controlled items, which could apply to AM should conditions be met.

Similar to the WA, the MTCR also has a “catch-all” export control clause to capture items that may not be explicitly listed in the Annex, but which could be used with delivery systems for WMD. Moreover, intangible technology related both to items included in the Annex and to the catch-all clause is also encompassed by the MTCR, although unlike the WA there is no publicly available guidance on this aspect.[120]

The **European Union Dual-Use Regulation** provides the regulatory framework for members states of the European Union on the control of exports, brokering, technical assistance, transit and transfer of dual-use items. The Control List of Dual-Use Items in Annex I of the Regulation includes references to metal AM equipment and related materials.[121] This list is reviewed and updated annually, and it usually aligns with the lists of controlled items developed by other multilateral control regimes, including the Australia Group, the MTCR, the Nuclear Suppliers Group and the WA. However, the latest update to the European Union Control List is broader in scope than the WA list – the divergence arises from political roadblocks in the WA. Similar to the WA, the EU Control List encompasses ITTs in the form of technical assistance and technical data, and also includes a “catch-all” provision for non-listed items.

Beyond the Dual-Use Regulation, the European Union Common Military List may also be applicable to military-specific (i.e., not dual-use) AM. The Common Military List notably encompasses software and technology, including technology for the production and development of items in the list.

The **United Nations Programme of Action on SALW**, which is politically binding on all United Nations Member States, resolves to “prevent, combat, and eradicate the illicit trade in small arms and light weapons”.[122] While the framework does not explicitly mention AM, or 3D printing, it requires states to exercise “effective control over the production” of SALW.[123] Outcome documents from recent meetings of states have highlighted the need to address the unregulated 3D printing of SALW.[124] The Fourth Review Conference of the PoA established an open-ended technical expert group (OETEG), which has been asked to consider how to ensure that 3D printing of SALW is covered by the PoA and the related International Tracing Instrument.[125]

Finally, the **Arms Trade Treaty**, which has 118 state parties, aims to regulate “the international trade in conventional arms and seeks to prevent and eradicate illicit trade and diversion of conventional arms”.[126] The ATT includes obligations for regulating international transfers of conventional arms, their parts and components and ammunition, but not their manufacture. In other words, the ATT does not differentiate between a UAV manufactured using AM and one manufactured using a different technique. ITTs are also not included in the scope of the Treaty.

5.2. Governance challenges and gaps

Despite the existence of arms and transfer measures that apply to AM technology, there are nonetheless challenges and gaps.[127]

The first issue, while not novel, is the **dual-use aspect of AM technology**. In other words, AM technology that is designed for civilian applications can be used for military purposes. This complicates the challenging equilibrium sought by export controls of ensuring sufficient oversight and addressing potential security concerns, without negatively affecting legitimate commercial applications or hampering innovation. For example, export control lists primarily include high-end AM printers and associated materials, especially those more likely to be involved in the creation of more highly controlled outputs, while omitting lower-end systems. While the latter could, nonetheless, be used to create items for use in a military context, they fall under the threshold determined by the given mechanism. Intent behind the use is a determining factor, but it is not always possible to ascertain this when undertaking risk assessments or updating control lists.

Second is the **ability to regularly update the multilateral control lists**. Regular updates to control lists can help ensure that they adequately reflect developments in technology, the enabling materials and potential applications. However, as in the case of the WA, some proposed changes have not been applied due to lack of agreement between the participating states.[128] Such situations can further fragment the export control landscape. While the membership of the different mechanisms overlaps, this may still result in different applications of controlled items depending on the state, and therefore companies may face challenges in adhering to different and inconsistent regulations. Despite this current challenge, these regimes continue to provide an important and critical platform for discussions and exchanges.

Third, ensuring **adequate controls over the transfer of intangible technologies is complex, and current guidance requires strengthening**. While this issue is not specific to AM, it remains important when discussing governance challenges regarding AM. Export controls have primarily been shaped around the transfer of tangible, physical goods, and as such are less adapted to ITTs.[129] ITTs pose a particularly important risk because of the challenges in the ability to control them. While many states and the WA provide guidance on ITT export controls, these are non-binding. This is reflected in states' varying approaches to and interpretations of ITTs and what they comprise. This lack of consistency has a detrimental effect on other actors involved in the production of weapons or their parts and components using AM.[130] Not only can this be challenging for companies to adhere to rules and regulations, which can differ between states, it also leaves unanswered questions on the scope of ITTs of AM technical data, such as whether and how specific IT providers or cloud use are regulated.[131]

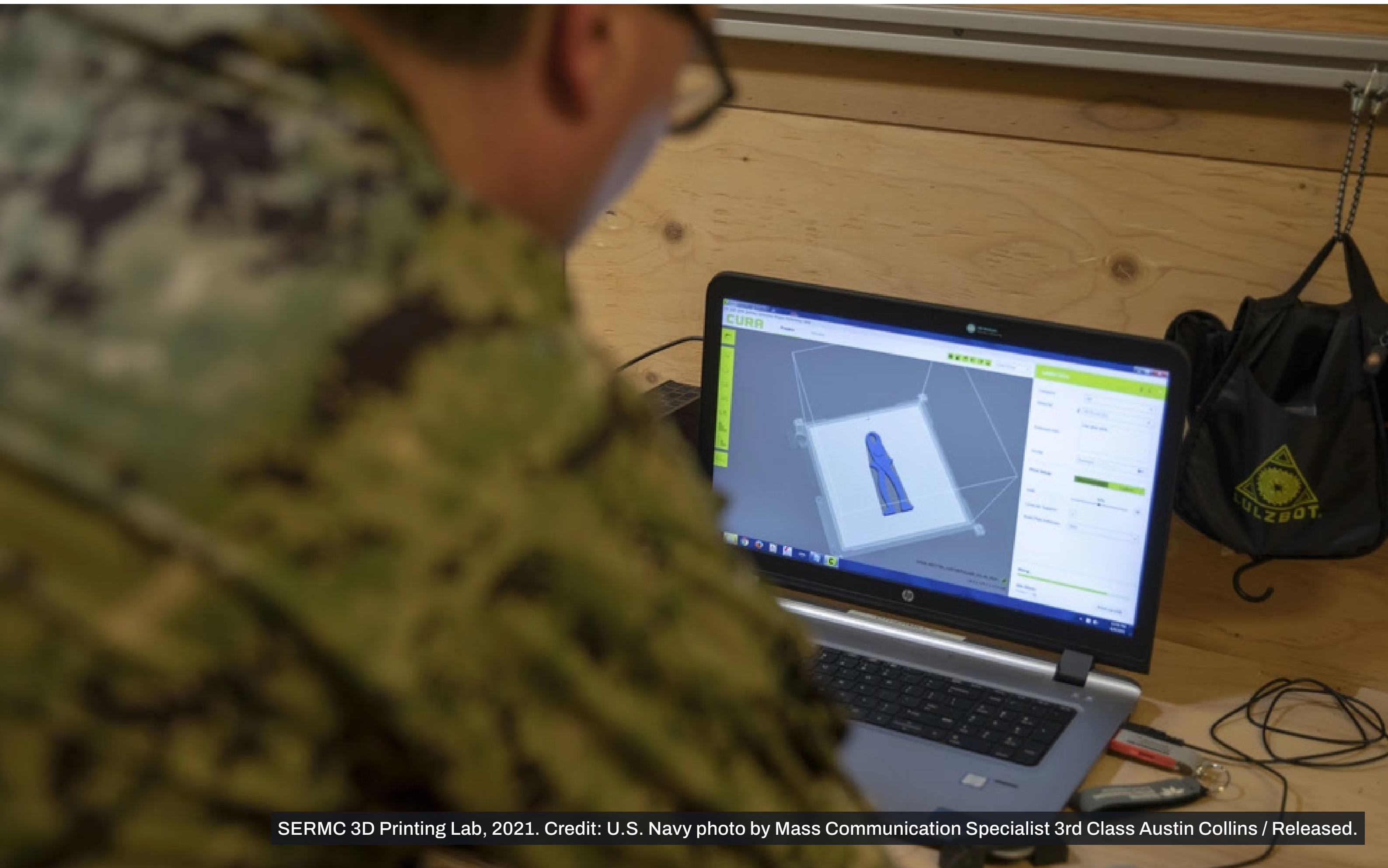
Finally, the **membership of the existing multilateral export control mechanisms is limited.** While membership of these mechanisms is not a prerequisite to adopting national-level regulation of AM, lack of member status prevents non-participant states from actively contributing to, and fully benefiting from, these mechanisms. More specifically, this can relate to the continuous sharing of experiences and good practices among participant states. This is especially relevant with regards to the challenges posed by ITTs.

6. Conclusion

The current trends in the technology, applications areas and actors involved in additive manufacturing indicate that it will continue to hold appeal for the production of conventional military equipment and their parts and components. The technology can enable the rapid production of tooling and prototypes and the rapid and mobile production of parts and components, and it can enable novel properties. Benefits therefore include greater operational readiness and resilience, reduced reliance on traditional supply chains, and improved performance of outputs.

There nonetheless remain open questions as to the extent to which its use can be expanded, given ongoing and as yet unresolved challenges in the standardization and certification of outputs or IP rights over the digital files. Despite that, and accounting for the fact that AM machines and techniques vary in terms of their uses and capabilities, the number of actors having access to or using this technology is increasing. AM of military equipment is no longer solely constrained to research institutions or for use by the defence-industrial base; it is also increasingly used by militaries themselves.

Adequate control of the different facets of AM to prevent illicit diversion and proliferation can be challenging. This includes accounting for the machines and their associated materials as well as the digital files and the knowledge and skills to produce AM outputs. AM technology is primarily governed through export control mechanisms, which notably need to account for dual-use considerations. This is occurring in parallel to increases in the number and type of actors involved in AM, not all of which will be familiar with the rules and regulations governing export of dual-use or military items, both tangible and intangible.



SERMC 3D Printing Lab, 2021. Credit: U.S. Navy photo by Mass Communication Specialist 3rd Class Austin Collins / Released.

While multilateral export control mechanisms and ongoing engagement within them remain key, complementary avenues for action merit further consideration. These can be grouped in three broad categories: strengthening the application of multilateral control measures; addressing gaps, limitations and challenges of national export control mechanisms; and raising awareness and improving industry compliance.[132]

6.1. Strengthening the application of multilateral control measures

The first category relates to elements that can strengthen the application of multilateral control measures. It includes the following.

Using the ATT framework to examine regulation of (intangible) transfers for AM of conventional arms

While the Arms Trade Treaty does not address arms production, AM developments could affect implementation of the ATT. As noted above, AM of conventional arms, particularly parts and components, could introduce new producers and supply chains for consideration under international transfer control instruments. ATT Article 4 on controlling exports of parts and components stems from concerns about the circumvention of treaty obligations in Articles 6 and 7.[133] AM provides a potential circumvention opportunity that is not currently covered by the Treaty. Therefore, the ATT framework, which has a broader constituency than the export control regimes, provides an inclusive dialogue platform for considering AM and intangible transfers. If the proposed informal group of interested states and stakeholders tasked with considering the scope of the ATT and national control lists is established, it could consider approaches for controlling international transfers relating to the use of AM for conventional arms.[134]

Establishment of international standards

Standards can define technical aspects of AM, the digital aspects (e.g., ensuring digital files are authentic, controlled, traceable and auditable), as well as the marking, serialization, qualification and certification of outputs.[135] As such, standards can complement regulatory measures by providing a foundation on which other avenues for action can build, as well as a framework with which export control mechanisms can work to identify and manage goods that fall within a given scope. A common misconception is that no standards exist. However, there are currently over 80 standards agreed by the ISO and ASTM International.[136] Whether and how to integrate existing standards would therefore be an area for exploration.

Practical and harmonized approaches to the regulation of transfers of intangible technology and their implementation

Clearer regulations and definitions and the development of practical voluntary guidance around ITTs could be beneficial to improve risk management stemming from the transfer of digital AM files.[137] As the lack of a harmonized approach has been raised as being an existing challenge, dialogue between states, as well as between states and other actors such as industry, could help with improved understanding of challenges and grey areas. Alongside these dialogues there should be a more consistent and practical application of regulations. This can include ensuring that relevant resources are made available more broadly beyond the membership of a specific mechanism.

Exploration of technological solutions

In parallel to existing regulations, technological solutions could be explored to address the diversion and proliferation risks. For example, whether and how illicit use of digital files could be interdicted through software (e.g., through the help of AI) or through techniques such as digital watermarking.[138]

Improving reporting on national production

Should the use of AM increase and become more widespread, with new producers, it would be worth considering how to mitigate the impact on transparency and confidence-building measures, such as UNROCA. This can include enhancing state reporting on procurement through national production.

6.2. Addressing gaps, limitations and challenges of national export control mechanisms

The second category focuses on the need to address gaps, limitations and challenges of national export control mechanisms. It includes the following:

Development of capacities to detect, prosecute and enforce regulations

It is important to act upon breaches of regulations for the export control of tangible and intangible AM technology. This ranges from early detection of diversion attempts, such as by screening foreign direct investments,[139] to having the ability to conduct digital forensics, translating these findings into evidence and having prosecutors specialized in the area.[140] A good understanding by states and national authorities of AM and the cyber-physical risks related to the technology is therefore important.[141]

Development of AM risk profiles

Risk profiles refer to understanding how risk differs according to the different types of AM technology, different types of output and user, and the circumstances that exacerbate risk. The risk emerging from AM differs according to a range of variables (as noted in Section 4). This can make it challenging to govern without hampering commercial uses and civilian applications. This can be addressed through creating risk profiles or scenarios, alongside other case-based approaches to understanding AM risk.[142] This can draw upon the established practice of use-case differentiation through parts classification – in other words, classification of outputs according to characteristics such as intended function and consequences of part failure – with different profiles linked to different qualification, inspection and oversight requirements. In an arms control context, risk profiles could help regulators to better assess which types of risk may be both more likely and more impactful, and to develop governance responses scaled to the consequence of failure or misuse, rather than applied uniformly. Such an approach would avoid overregulation of the underlying manufacturing technology.

6.3. Raising awareness and improving industry compliance

The final category relates to the importance of industry responsibility in mitigating risks from AM, and notably from ITTs. It includes the following:

Awareness-raising and capacity-building of actors involved in AM

Awareness by states of the need for actors involved in AM, in particular industry actors, to abide by existing regulations can help address unintentional non-compliance. More practical guidance would be beneficial, as would training on issues such as the dual-use implications of AM technology and export control considerations, especially for small firms or newcomers in the defence sector.[143] Greater enforcement of controls, investigation and prosecutions of transgressions will also play a role in raising awareness.

Industry due diligence

While there is a need to ensure that compliance can be made easier by states through clearer and more practical regulations and guidance (as discussed above), industry actors, including non-traditional defence contractors, should also apply adequate due diligence to prevent and mitigate risks posed by AM technology. This can include, but is not limited to, applying trusted distributed-manufacturing approaches (e.g., certified production nodes operating with controlled access to files); adapting or creating guidance specific to AM, such as on adequate processes for supply chain control (for both subcontractors and customers); implementing internal awareness-raising and training; verifying whether import or export licences are required; and securing the (digital) data flow, such as properly managing restrictions on access to relevant servers or data and implementing audit trails.[144]

Traceability of AM supply chains

Keeping track of supply chains, especially for transfers of digital AM files, improves not only transparency but also risk management. This can include keeping track of what has been transferred, on what date and at what level of classification[145] – in essence, keeping a "chain of custody" related to the transfer of AM technology.[146]

Annex I. List of interviewees

The authors are grateful to all experts took part in the research interviews and for the information they contributed.

NAME	POSITION AND AFFILIATION	DATE
Dushyant Dubey	PhD researcher, Indian Institute of Technology Delhi	19 November 2025
Jonathan Meyer	CEO, APWorks [at time of interview]	21 November 2025
-	Ziggzagg staff member	25 November 2025
Barrett Veldsman	Founder, DEFEND3D	27 November 2025
Anonymous expert	-	28 November 2025
Kolja Brockmann	Independent consultant and Senior Researcher (non-resident), SIPRI	1 December 2025
Lotte Bruynen	Director, Export Compliance & Sanctions, Deloitte	5 December 2025
-	Representative from Cranfield University	10 December 2025
Mohsen Seifi	Vice President, Global Advanced Manufacturing & CET Division, Principal Investigator, Advancing Standardization for Critical and Emerging Technologies Center of Excellence, ASTM International	12 December 2025
Sandeep Singh Klair	Researcher, Norwegian Defence Research Establishment	2 February 2026
Bendik Sagsveen	Scientist, Norwegian Defence Research Establishment	2 February 2026
Rosa Rosanelli	Vice President, Head of Compliance, Patria	5 February 2026
Arun Seraphin	Executive Director, Emerging Technologies Institute at the National Defense Industrial Association	10 February 2026

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