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# Application of Printed Electronics in Guided Explosive Ordnance Systems

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To be a potent and credible military force, the Australian Defence Force must be able to manage the strategic risk for identifying the requirement for 'minimum viable capability in the shortest possible time'. Modern explosive ordnance relies heavily on electronic components, which are currently not manufactured within Australia. Here, we explore the potential of using printed electronics to enable rapid development of a manufacturing capability to supplement the domestic manufacture of guided weapons and explosive ordnance.

## 1. Introduction

The need to modernise Australian explosive ordnance (EO) manufacturing and supply has been at the forefront of every defence strategic review over the past decade. The sense of urgency that accompanies the current principles of speed to capability and minimum viable capability outlined in the *National Defence: Defence Strategic Review* (DSR) (Houston & Smith, 2023) provides the conceptual framework that will define progression of EO manufacturing capabilities in the near term.

Long-range strike and guided munitions, especially expendable drones, are considered fundamental weapon systems in the Australian Defence Force (ADF) inventory that define it as a credible and potent military force. The majority of modern EO systems, including unguided munitions, contain electronic components and, in all cases, are required in much greater quantities than defence industry can manufacture or acquire from global sources.

Acute supply chain stress and global demand constitute an undisputable problem and the ADF cannot maintain the *status quo* on EO manufacture and supply. The Guided Weapons and Explosive Ordnance (GWEO) Enterprise facilitates a deliberate, comprehensive and holistic approach to shore up ADF holdings of required EO stocks. Industry access to emerging manufacturing technologies will contribute to the solution. In its current level of maturation, printed electronics are not able to meet the quality control standards for integration in EO systems. This could be overcome through research and development, collaborative technology sharing, and incentivising electronic printing industries to introduce the benchmark for conforming printed components into the supply chain.

Historical and current examples of conflict (particularly the war in Ukraine) demonstrate the unsurprising, yet extraordinary consumption of EO stocks during combat operations. Joint concepts such as Multi-Domain Strike and Integrated Air and Missile Defence increase the demand for highly sophisticated guided weapons supplied to Australia via the global market. However, there remains a need for vast quantities of unguided weapon systems, which is modestly treated by growing sovereign EO manufacturing initiatives such as the Rheinmetall NIOA munitions joint venture (Leben, 2022).

Advanced manufacture initiatives offer substantial improvement of production cost, material efficiency and means to mitigate the strains of unpredictable supply chains (Falconi, 2023). One embodiment, additive manufacture, commonly known as three-dimensional (3D) printing, is capable of rapidly generating complex structures with minimal wastage (Lyu et al., 2021). Implemented since the 1980s, recent advances have allowed the ability to print objects with electron transfer properties – that is, the ability to print entire self-functioning electronic circuits in a single print run (Gaget, 2018). Such capability should be enticing to a country that is reliant on vulnerable international supply chains.

Applications in global military and space industries are maturing electronic printing capabilities. In the late 1990s, the United States (US) Defense Advanced Research Program Agency (DARPA) generated the Mesoscale Integrated Conformal Electronics (MICE) project to develop tools that would take electronic printing from 2D (essentially paper printed) to multi-material, design conformal electronic components directly from computer-aided design models (Optomec, 2020). Maher et al (2014) claim DARPA's investment in additive manufacturing is progressing from development and demonstration to widespread application, noting that limitations and gaps still endure. A similar program exists in the National Aeronautics and Space Agency (NASA) known as the In-Space Manufacturing Project, which seeks to harness 3D printing along with other material manufacturing processes in support of deep space exploration missions (Prater et al., 2019). Of further relevance to defence planners was US Deputy Secretary of Defense Kathleen Hicks' August 2023 Replicator initiative call to leverage autonomous platforms that are 'small, cheap and many'

(Hicks, 2023), harmonising with the DSR's focus on asymmetric warfare.

Persad & Rocke (2022) describe the strain on the global electronics sector as a driving incentive to develop systems that fall under projects like the DARPA-MICE and the NASA In-Space Manufacturing endeavours. Acute negative impacts on supply of electronic assemblies and distribution of critical minerals, gases and chemicals (particularly those in semiconductive microchips) have bolstered the potential of 3D printing to redefine the electronics ecosystem. One example is to seek an alternative to the traditional electronic assembly method of using semi-autonomous processes to install separately manufactured components onto a printed circuit board. Instead, efforts should focus on developing machines and processes capable of multi-material 3D printing (MM3DP) to generate complete and functional electronic assemblies in a single print run.

Common across all methods of electronics printing techniques is the application of conductive, semiconductive and insulating material inks deposited in structural layers to create functional electronic components (Wiklund et al., 2021). Furthermore, printing offers unique benefits and methods that cannot be achieved with conventional electronics manufacturing, albeit within certain limitations. While it has benefited research and prototyping, to the best of our knowledge, there is yet to be an example of a complete printed circuit as part of an EO system, therefore, it largely remains theoretical. It will require deliberate investment to shape electronics printing into a viable production method and, therefore, a strategy must start with a clear demand signal to experiment with printed electronics and their application in EO systems.

Here, we analyse emerging electronic printing technologies and assess the viability for integration into ADF EO systems. We recommend potential pathways to remediate, reinforce and revolutionise the sovereign EO manufacturing process and consequently improve stockpiles to ensure strategic objectives of the ADF are met.

## 2. Explosive ordnance breakdown

### 2.1. Energetic systems

Propellants and pyrotechnics aside, the intended result of an EO system is often a detonation – where the explosive material is decomposed via the passage of a shockwave in a supersonic, self-sustaining exothermic combustion (Akhavan, 2011). This shockwave may then be leveraged to deliver a variety of outputs in ordnance as varied as shaped charge jets, hypervelocity fragments or enhanced blast effects. Regardless of the EO type, this effect is usually the result of high explosives constituting the main charge (Mathieu & Stucki, 2004). Electronics do not generally play a direct role in the thermochemistry process, however in modern systems, electronic components and sub-assemblies within the EO system are engineered to control or guide the delivery of high explosive effects.

Since the discovery of black powder, the first energetic material, militaries have sought to harness and control the application of explosives. The ideal military explosive is powerful in its energy release, must be safe to handle, can be stored for long periods of time and will only detonate under deliberately controlled conditions (Mathieu & Stucki, 2004). The overall design of any one type of EO system focusses on a threat to destroy, disrupt or affect. There is, however, always a trade-off between lethality, practicality and safety. Controlling this trade-off in EO is the explosive train, comprising a fuze, a booster and a main charge.

A fuze or firing device will initiate the explosive train and is the sub-system responsible for the safety, arming and firing functions (Jeong et al., 2018). The fuze is designed to perform under the right conditions when a certain stimulus is met. The stimulus can be in a form of physical contact with the target (as per point or base detonating fuze), or electrical impulses generated from a capacitor or battery upon receipt of a sensor actuated electronic firing sequence. Examples include acoustic and magnetic influence sensors, proximity and electronic time delay fuzes.

To initiate an explosion, sufficient energy must be transferred to the main charge material commensurate to its reactant output rate (Zukas & Walters, 1998). In typical military EO systems, an explosion is generated by detonators and boosters, usually built into the fuze along with safe-to-arm and firing mechanisms. A detonator contains primary high explosives that are sensitive to energy transfer, although in small enough quantities to allow for safe handling and transportation, reducing the chance of unintentional or accidental initiation. Triggering these primary explosives often leverages electronics, as we shall soon discuss.

The exploding detonator transfers energy to a booster – an explosive material less sensitive than the detonator, though incrementally greater in weight to ensure sufficient energy is transferred to the main charge for optimal performance. The main charge, as the name suggests, stores the vast bulk of the energy released upon functioning of the piece of EO.

### 2.1. Electronic systems

Electronics control and shape the flow of electrical energy via custom-built circuitry to perform a specific function (Ross et al., 2010). This is true in EO systems, where an electronic circuit in a projectile fuze contains a combination of conductors, semiconductors and dielectric components that form batteries, switches, transmitters, relays and logic circuits to control and initiate the explosive train and ultimately produce the final effect.

The power supply is an essential electronic component consisting of batteries or generators that power electronic circuits found in the fuze as well as in guidance and control systems. In addition, power supplies in various EO systems must be able to power a circuit in a missile or projectile in flight. Most missile flights are less than 20 seconds and much less for projectiles. Power supplies must be able to provide standby power of EO systems to endure up to ten years of storage and shelf life.

Electronics fulfil a pivotal function in precision guidance munitions. This includes information transmission from antennas and receivers for processing telemetry data and use of electronic signals to guide actuators in a control system to steer the munition (R. G. Lee et al., 1998). Increasing complexity of electronic systems ultimately leads to (semi)autonomous control systems for EO requiring tens of millions to billions of transistors. Such circuits leverage nanometer-scale fabrication techniques, requiring specialised equipment, produced by only a handful of entities globally. In contrast, we argue that printed and additively-manufactured electronics are slightly larger and applicable to the mass manufacture of relatively simpler EO that are currently dominating the battlespaces of Ukraine and the Middle East.

## 3. Current and emerging electronics printing

Printing electronics, along with other means of additive manufacturing, offer the potential of increased functionality while reducing time, cost and complexity of the parts being constructed (Goh et al., 2018). It is generating momentum and maturing beyond its reputation as a platform limited to research, development and prototyping (Marchese, 2021). The fundamental process present in all electronic and 3D material jetting technology involves printing of conductive and insulating inks onto a substrate. Printers employ various techniques that are suitable for different structures.

### 3.1. Printing materials

**Substrate.** The substrate is the base on which the inks are arranged and dispersed according to the printing technique being utilised. Therefore, the substrate material must prevent thermal and electronic interference from conductors and semiconductors. The dimensional stability of the substrate is important, as cracking or porous surfaces could compromise electron flow. This is particularly important when considering integration into EO systems, as the substrate (along with delicate electrical components) must withstand considerable force, inertia and temperature variations and stressors the system will be exposed to in its life cycle.

Recent advances in the quality of conductive ink are edging the industry closer to scalable commercial-grade printed circuit boards and flexible hybrid electronics (Slep, 2023). Wiklund et al (2021) and Khan et al (2020) describe how several kinds of inks are required to print a functional electronic component. When considering basic electronics theory, a structure requires conductive and semiconductive materials to allow the flow of electrons, and dielectric material to reduce or block electrical spillage. These properties allow for categorisation of inks as outlined by Lee et al (2020).

**Conductor.** The most common conductive inks are formulated from metals such as aluminium, silver, copper and gold. Different metals will degrade at varying rates when reduced to nanoparticle size. Carbon-based conductive inks and ceramics have also been formulated.

**Semiconductor.** These materials underpin the manufacture of transistors, which are key to advanced electronic devices. Silicon and germanium are among the common semiconductive inks, formulated from polymer blends and solvents.

**Dielectrics.** Dielectrics are used as insulators and in the fabrication of capacitor layers in electronics and therefore must be printed in substantial thickness to prevent electrical leakage. Ceramic oxides are formulated into dielectric inks; however, they are brittle and prone to cracking. The material used for substrates such as cellulose, gelatine, shellac and silk possess dielectric properties.

**Ink Formulas.** Recent advances in printable metal and insulating inks have transformed the scope of printed electronics to feasibly print sensors, circuits and devices straight off the printing line (Kahn et al., 2020). Ink recipes are crucial, where elements are refined to nanoparticles and combined with binders, solvents, surfactants and additives to provide the properties appropriate to the printing technique.

### 3.2. Printing techniques

The techniques and methods below are drawn from works of Khan et al (2020), Wiklund et al (2021) and Tan et al (2022). The two common categories are contact (also known as mask-based) and contactless (or direct-ink writable).

**Contact printing** requires the substrate to come in direct contact with the printing instrument. These techniques are utilised in large-scale printing, similar to a product label or magazine printing line. When used for printing electronic circuits, this technique is optimal for printing 2D circuits on soft and flexible substrates common in wearable devices.

Gravure printing is a form of contact printing where the ink is applied to a 'gravure' cylinder, engraved to produce the desired image or pattern. The substrate is rolled through the cylinder, which transfers the ink pattern onto the substrate. This is a common method for high speed, high-resolution 2D prints; however, the initial setup and engraving of the gravure cylinder can be time consuming and costly. Gravure printing is suitable for printing organic semi-conductors and dielectric interfaces.

Flexography is a form of contact printing where it employs flexible plates. The surface of the plate is sub-divided into pixels, which can be applied with an ink via an anilox roll (or series of rollers). The method of ink application is what differentiates this method from gravure printing.

Stencil or Screen printing is a form of contact printing where the ink is pushed through a screen or fine mesh made of plastic or metal fibres. The non-image areas (spaces where the ink is not desired) are stencilled and overlayed over the screen allowing ink to pass through and form the pattern as designed. The technique does not provide high quality prints but is a great choice for printing basic circuit components such as resistors and capacitors. Screen, flexography and gravure techniques have been described as capable methods for printing lightweight antennas, such as the Ultra High Frequency antenna printed by Thielens et al (2018).

**Non-Contact printing** is also referred to as direct-ink writeable (DIW). In this technique, there is no physical contact between the substrate and the ink is applied via a nozzle in a pre-determined digital design pattern. Tan et al (2019) describes the most common DIW methods to include inkjet, aerosol and extrusion-based printing.

Inkjet printing is a method commonly associated with standard day-to-day printing, where the ink is dispensed via a nozzle or series of nozzles onto a substrate according to a digital design pattern. Inkjet prints at high resolutions, at slow speeds and consumes less ink. Wiklund et al (2021) describes inkjet as the most extensively employed technique for depositing inks directly onto substrates.

Aerosol printing involves accurate and delicate application of atomised ink droplets that are in the order of micrometers in diameter. Atomisation occurs via a pneumatic or ultrasound chamber, which reduces clogging and other mechanical errors. Aerosol prints at a slightly slower rate than inkjet printing. Thielens et al (2018) describe aerosol, or 'spray', printing as offering balance between cost, accuracy and flexibility, suitable for prototypes and smaller batches of customisable components. Further, the printing technologies contributing to mature MM3DP (as described by the DARPA-MICE project) utilise aerosol methods since it is a practical method catered for multiple ink types (Optomec, 2020).

### 3.3. Examples of printed electronic components

The basic principles of energy storage often constrain design; however, these could be overcome with the emergence of printed batteries. A study conducted by Singh et al (2012) demonstrates the successful application of using 2D printing (or 'painting' as described in the study) to produce functional batteries. The components of any battery include the electrodes, current collectors, the electrolyte and plate separators. In their report, a functional lithium-ion battery was produced by applying battery material to various flat surfaces via an airbrush. The principles applied in Singh's report could be replicated to manufacture miniaturised versions for EO fuze systems.

Choi et al (2021) posit that missile accuracy is largely affected by the performance of the guidance system. In their report, they produced a printed Yagi-Uda antenna as the base structure, modified with a half wavelength director to focus the antenna beam width and enhance the ability to receive and transmit signals in a particular direction. Their printed antenna is a pronged array of elements commonly associated with the Yagi-Uda. The study concluded that such an antenna could be utilised as a radar antenna for a guided missile.

The antenna printed by Choi et al (2021) operated in a Super High Frequency band of 9.375 GHz with wavelengths of about 32mm. Another example of a printed antenna is the aerosol spray printed 800-900MHz Ultra High Frequency antenna fabricated by Thielens et al (2018). This type of device is useful for radio frequency identification and tracking (such as supply chain or inventory management, factory assembly monitoring and transportation). While not immediately applicable to current EO systems, through iterative research and development, such methodologies could be applied to the production of tracking and guidance devices on large numbers of low-cost guided weapons or loitering munitions.

Modern EO systems require integrated circuits to manipulate and control electronic signals to perform certain functions. A 555 timer is an example of such a circuit. Developed in the 1970s, they are more common in commercial or household electronics and legacy military systems with more sophisticated circuits incorporated in modern EO natures today. Their simplicity, however, offers advantages in the manufacture within a 'many, small, attritable' systems paradigm. Marston (1990) outlines the circuit operation, by controlling pulses along resistor-capacitor (R-C) networks in monostable (regular pulse generation) and astable (continuous oscillating square wave) modes of operation. EO examples include timed pulse oscillators (present in radar and proximity systems), sensor queuing (activating a pre-firing sequence in a magnetic influence fuzed loitering munition) and actuation (electronic initiation of an explosive train).

An example of a printed 555 circuit was produced by Lopes et al (2012) over a decade ago. The component was produced using a stereolithography printer to generate the circuit housing in stages, where electronic components were inserted and then encased in additional printed layers. While the electronic components themselves were not printed, it is an example of semi-autonomous multi material fabrication. It is foreseeable that this type of build could be manufactured using MM3DP principles in the near future.

The examples of printed batteries, antenna and electronic timers illustrate the potential of using 3D printing systems to produce essential electronic components in EO systems. It demonstrates that while concepts are understood and functional components can be produced in isolation, iterative developments should focus on miniaturisation and robustness to allow for integration into EO fuzes or other sub-systems.

### 3.4. Application in explosive ordnance

The advantages and disadvantages of each method described above largely depend on the feature size being printed and the manufacturing rates required (K.-H. Lee et al., 2020). If it is assumed that the required component dimensions for EO electronics are in hundreds of microns to millimetres, the most suitable printing techniques are screening, aerosol spray, inkjet and extrusion-based. However, the selected printing method will address the production need, thus other techniques may be more applicable. For example, the ability to produce gravure-printed reels of photovoltaic cells for energy harvesting may be very useful as auxiliary power supplies for loitering munitions. Similarly, autonomous systems, requiring sub-micron feature lengths, will likely leverage short-wavelength photolithography.

## 4. Australian industry capacity – limitations and opportunities

The urgency to deliver the DSR outcomes pertinent to ADF EO holdings and manufacture implies a short-term focus on rapid acquisition of foreign off-the-shelf EO systems. The pace of change in strategic circumstances, however, demands a deliberate strategy to pave a way to reliable, sustainable and efficient domestic EO production as soon as possible. While Australia will not be printing electronic components for EO at national infrastructure scale in the immediate future, the technologies are clearly worthy of further investigation in a rapidly changing world.

We analyse Australian industry capacity for integrating 3D printed technology with EO system production. First, the current sovereign EO enterprise and Australian electronics sector need to be examined. And second, the barriers accompanying 3D printed electronics manufacturing must be assessed to derive plausible incentives and drivers for industry.

### 4.1. Current explosive ordnance enterprise

The Commonwealth owns two main production forges that are contractually managed and sub-leased by industry partners in Benalla (Victoria) and Mulwala (New South Wales) (Ziesing, 2018). These facilities produce small arms, medium calibre projectiles, hand grenades, explosive fills and propellants. They also facilitate EO research and development and test and evaluation. In addition, the Maryborough (Queensland) forge operated under the NIOA and Rheinmetall Waffe Munitions joint venture can manufacture the German-owned 155mm Assegai munitions and distribute the suite of Junghans fuze systems (Leben, 2022). It produces 155mm natures under a munitions deed as part of Land 17 Advanced Artillery Munition Systems for towed artillery platforms, while supplying the global export market (NIOA Group, 2023). Industry primes contribute to multinational partnered guided weapon systems by producing certain components, though Defence is driving towards complete missile production by 2025 (Tillett, 2023). The cost incurred to maintain these manufacturing facilities is up to three times greater than the value of munitions produced by them (Leben, 2022). This emphasises the long-term investment requirements for sovereign EO manufacturing – the returns in value may not present themselves for decades and, therefore, Australia must be committed to, and focused on, mitigating strategic risk, not project risk.

There are two key observations from the analysis of Australia's current EO enterprise. First is the production emphasis on propellants, explosive fills and small-medium ammunition calibres and the absence of fuze production. Secondly, any future developments in fuze production of foreign systems will be under strict licensing and intellectual property handling agreements. As a relatively small customer, Australia will not have the leverage to alter manufacturing methods and adopt 3D printed electronics for these systems. Therefore, sovereign industry will be constrained to the current methods of importing electronics, semiconductors and printed circuit boards for assembly on production lines. Thus, the Australian electronics sector and supply chains must be examined.

### 4.2. Current electronics enterprise

Australia's electronic and semiconductor manufacturing will contribute modestly with opportunities to productionise technologies in the long term to build a sovereign semiconductor manufacturing presence (Smithurst, 2023). Until then, the Australian market will rely on imports from Taiwan, the United States, South Korea and China as the global suppliers in semiconductor production (Leslie, 2022). It is unlikely Australia will become a global leader in electronics manufacturing despite the contributions in securing access to electronics supply and growing sovereign production. The Australian electronics sector will remain dependent on critical supply chain risks and must consider sufficient risk mitigation strategies.

The reliance on global markets for production of microchips, integrated circuits and critical semiconductors is exacerbated further by the paucity of raw materials (Dwivedi & Wischer, 2022). Current manufacturing methods rely on approximately 30 critical minerals, including high volumes of silicon and gallium arsenide with cobalt becoming increasingly important (Dwivedi & Wischer, 2023). According to a study conducted by Althaf & Babbit (2021), at-risk materials relevant to printed electronics include silver, gold, cobalt, gallium, platinum and tantalum. It is therefore false to assume that supply chain issues are resolved entirely by adopting additive manufacturing methods. In most cases, the supply chain is simply redefined or diverted with the possibility of creating new supply chain dependencies. The demand for critical materials will endure for printed electronics either in raw form or manufactured as inks.

A significant limitation and barrier to 3D Printing of electronics in EO systems is the heavily regulated nature of EO safety requirements. The North Atlantic Treaty Organisation (NATO) Munition Safety Information Analysis Center (MSIAC) has yet to produce a report on implementing 3D printing electronics in munitions. In a NATO MSIAC paper on using additive manufacturing for munitions, Babcock (2018) highlights that the introduction of novel production technologies is inherently accompanied by the introduction of new flaws and defects associated with new material properties. While this is directed at structural components of munitions, it is even more critical when considering electronics are responsible for safe-arm functions, guidance and control sections. Furthermore, the ink layers and methods of adhesion result in residual stresses which may cause problems during EO system launch, in flight and terminal ballistic stages (Marchese, 2021).

It is assumed that any modification and deviation in the manufacturing method of in-service EO systems must be managed by the entity that owns the IP and must be certified to relevant safety benchmarks. Consequently, Australian defence industry does not have the leverage to alter the design or production process of any EO system as it is only licensed to produce on behalf of the foreign manufacturer. Therefore, transitioning to additive electronic printing is much more feasible if efforts are focussed on next generation munitions where electronic components are inherently designed for production *via* additive manufacture methods.

While these limitations appear colossal, it is proportionate to the advantages and opportunities presented by transitioning to 3D printed electronics. Cooper and Hughes (2020) emphasised that additive manufacturing has revolutionised the way systems are designed and produced, largely due to the electronics industry continuously seeking out advancements to reduce unit cost, energy requirements and material overheads. There have been significant advancements in electronics printing in wearables, human performance and medical sectors since current technology readiness is suitable for flexible hybrid electronics. Sovereign industry has been able to leverage expertise from academic entities like the Australian Nano Fabrication Facility that specialise in providing maker spaces for research and prototyping. Allocation of industry resources and grants could focus on the miniaturisation and ruggedisation of proven printable electronic components, in a similar manner to the production of the proximity fuze during World War II (Baldwin, 1980). However, it may require international collaboration to generate a holistic design and at-scale production strategy. There is opportunity to merge electronics printing with advancements in energetic material printing and structural additive manufacturing for end-to-end 3D printed munitions.

## 5. Conclusion

There are significant challenges and barriers in adopting electronic printing methods for EO that, in other than niche applications, are currently beyond Australian capacity to overcome. It will take a combined effort to harness the potential of additive manufacturing for optimal production of EO systems. Additive manufacturing is fundamentally changing the way commercial everyday items are produced and, while the use of 3D printers is not new, the application of printing technology has the potential to revolutionise aspects of the Defence capability acquisition process.

Electronic printing methods have been examined, highlighting practical applications in EO systems and providing examples of functional printed components. To produce functional inks, manufacturers will require access to the same high-demand critical minerals that define the acute supply chain stress in the current electronics market. Therefore, while the supply demand is treated in one area, there are new and existing dependencies associated with printed electronics production, which may be mitigated by uplift in other domestic capabilities.

We conclude that the components that will benefit most from printed electronics are batteries, fuze systems, guidance components and sensors. The critical safety requirements in these systems are heavily regulated with centrally controlled safety benchmarks beyond Australian sovereign industry influence. These factors all contribute to the pathway forward to shore up domestic manufacturing of munitions to ensure the ADF is equipped to achieve its strategic objectives.

In the near term, the Commonwealth will need to exercise a *speed to capability* approach to reconstitute EO stocks through current munition contracts and foreign military sales. However, 10 to 15 years from now, after the immediate glaring capability gaps are closed, sovereign EO industry could look very different. It could expand significantly from a handful of ammunition production forges to dozens of licensed manufacturers capable of printing components on demand, offering scalability and redundancy.

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