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Preventive Arms Control for Small and Very Small
Armed Aircraft and Missiles

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Small and Very Small Armed Aircraft and Missiles: Trends in Technology and Preventive Arms Control

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Abbreviations and Acronyms

AI	Artificial intelligence
AWS	Autonomous weapon system
CCW	Convention on Certain Conventional Weapons
CFE	Conventional Armed Forces in Europe
DSF	Deutsche Stiftung Friedensforschung (German Foundation for Peace Research)
CPU	Central processing unit
GLONASS	Global Navigation Satellite System
GNSS	Global navigation satellite system
GPS	Global Positioning System
GPU	Graphics processing unit
HCoC	Hague Code of Conduct against Ballistic Missile Proliferation
IMS	Inertial measurement system
MANPADS	Man-portable air defence system
MTCR	Missile Technology Control Regime
RAM	Random-access memory
UAV	Uninhabited/uncrewed aerial vehicle
UN	United Nations
US(A)	United States (of America)
WiFi	Wireless Fidelity
WMD	Weapon of mass destruction

1 Introduction

The project 'Preventive Arms Control for Small and Very Small Armed Aircraft and Missiles', funded by the German Foundation for Peace Research (DSF), has investigated the properties to be expected of ever smaller aircraft and missiles, including their use in swarms.[1] Small and very small aircraft (armed or not) are treated in report no. 1 from the project (Pilch et al., 2021a, b), small and very small missiles (virtually all armed) are the subject of report no. 2 (Altmann & Suter, 2022a, b). This final report no. 3 covers technological trends and discusses preventive arms control for both areas.[2]

The report is structured as follows: Chapter 2 presents technological trends, looking at relevant areas. Readers not interested in the technological aspects can skip it. Chapter 3 treats military-technology assessment, subjecting both kinds of small systems to the criteria of preventive arms control, and presents options for preventive limitations and for verification of compliance therewith. Chapter 4 gives a short conclusion with recommendations for international action.

1 https://url.tu-dortmund.de/pacsam; overview in (Altmann et al., 2022).

2 Preliminary arguments have been given in (Altmann et al. 2022: sections 5 and 6).

2 Technological Trends

Technological trends are one part determining the future developments in small, armed uninhabited/uncrewed aerial vehicles (UAVs) and missiles (the other parts being military interests in and resources devoted to them). At the start of the project the intention had been to describe the technological trends with a view to what could arrive five to ten years, and what in ten to twenty years. However, during the project it turned out that such differentiation would need more work than possible in the available time. Thus a wider view was chosen, and particular attention was given to possibilities of further miniaturisation. The following sections treat various areas from microelectronics to energy supply and propulsion, take a short look at swarms and swarm control, and then discuss downscaling of UAVs and of missiles.

2.1 Microelectronics

Further increasing computing power and memory capacity ("Moore's law") by shrinking component size on a two-dimensional silicon chip is arrriving at a limit as the sizes approach atomic levels and power consumption becomes a problem (e.g. Theis & Wong, 2017). The semiconductor industry pursues several different paths to nevertheless increase the component density, e.g. by three-dimensional structures; the International Technology Roadmap for Semiconductors (last issue 2015, ITRS, 2015) is being replaced by the International Roadmap for Devices and Systems (IRDS, 2021a, b, c, d; Gargini, 2017). Therefore it is to be expected that computing and memory performance will continue to grow for at least one more decade.

This can be used to further enhance the processing power and memory size of normal-size equipment, or to allow further miniaturisation at equal or even improved capabilities. The latter will get a strong boost by the internet of things and by smart phones. In the areas of small and very small aircraft and missiles the consequences can be that systems with unchanged size get markedly more capable algorithms, e.g. for using artificial intelligence (AI), in target recognition or in situation assessment. On the other hand, smaller and more light-weight control systems will allow further reduction of the size of UAVs and missiles, without significant loss of processing power.

The present possibilities are visible in two extreme cases. There are tiny microcontroller boards the chips of which provide impressive capabilities. One example is the Adafruit QT Py RP2040 with dimensions 22 mm · 18 mm · 6 mm with 2.2 grams mass.[3] The dual-core processor of 7·7 mm^2 package, introduced in 2021 by Raspberry Pi, can run with 133 MHz, has 2 MB flash memory and 264 kB RAM and can be used for sensing, actuating and controlling tasks (Adafruit 2022; Raspberrry Pi, 2022).

3 Similar boards are offered by e.g. Raspberry Pi and Arduino. Note that such controllers and single-board computers are sold very cheaply and are widely used by hobbyists. All kinds of add-on sensors are available; usable for navigation are e.g. inertial-measurement, Global Positioning System (GPS) and camera units.

At the other end are system-on-chip processors built into high-end smartphones. E.g. the Apple A15 Bionic (package about 40·30 mm^2), likewise introduced in 2021, manufactured in a 5-nm process, has nearly 16 billion transistors, 6 central processing unit (CPU) cores and 5 graphics processing unit (GPU) cores.[4] The CPU clock rate is up to 3.2 GHz (Apple, 2022; Hinum, 2021). Circuit boards inside the 142·72 mm^2 housing hold about 25 additional chips for the various services (such as display, camera, WiFi, GPS). Their mass should be around 13% of the phone mass of 173 g (Singh et al., 2018), that is around 24 g.

With respect to further miniaturisation of aircraft and missiles one can cautiously extrapolate that in ten years the processor and board of the first example could fit into a size of a few millimetres and below, with a mass of few tenths of a gram. The very sophisticated capabilities of the second example might be possible in a space of few centimetres with a mass of few grams. However, this assumes that specific developments for very small military systems would be done – removing unncessary civilian components and better fitting processor and periphery into a thin body.

This means that seen from the computing side UAVs and missiles with 10 mm body diameter may become possible and get sophisticated capabilities for navigation, target recognition and reaction to circumstances. Whether this can materialise hinges on the other components such as propulsion, energy supply, sensors etc. – and on the expected military utility.

2.2 Guidance Systems – Inertial Measurement Systems (IMS)

Navigation, that is determining the position and controlling the trajectory of a vehicle, in the air in three dimensions, can be done without any external signals by measuring the direction and magnitude of the inertial force that an object is subject to – e.g. from its propulsion, from air drag or from wind. Usually the three-dimensional force is measured by orthogonal accelerometers while the three-dimensional rotation (angular) velocity is gained from three gyroscopes. With known initial position, velocity and heading, integration of the rotation velocity gives the momentary heading, and integrating the acceleration over time gives the momentary velocity, further integrating this yields the momentary position. Since the measured force includes the earth gravity, this has to be subtracted, in sophisticated systems using a detailed model of the gravity field as a function of geographical position and altitude.

Traditional inertial sensors used macroscopic mechanical components, later ring-laser or fibre-optic gyroscopes were introduced. Both types are still used in high-precision applications. For less demanding requirements since a few decades sensors using micro-electro-mechanical systems, mass-fabricated in silicon similarly to microelectronics, have become common, allowing strong miniaturisation (e.g. El-Sheimy & Youssef, 2020). IMS sometimes also include three-dimensional magnetometers acting like a compass.

IMS of millimetres size and gram mass are being used e.g. in smartphones. Their commercial-grade accuracy suffices to detect the orientation of the phone and react to arm

4 Similar processors are offered by e.g. Qualcomm, Mediatek and Samsung.

movements, but the offset and drift are too big for use in aircraft or missiles. For these, tactical-grade IMS are needed, with typical positional-error rates of 19-37 km per hour, a gyro drift of 1-10 °/h and an accelerometer bias of 0.01-0.05 m/s^2 (El-Sheimy & Youssef, 2020, Table 1).[5] The accumulated error for a small UAVs of several ten minutes endurance will be larger than that of a small missile over its several-seconds flight time, but may suffice to take the system to the intended region. In many cases IMS drift is corrected by absolute position determination using signals from global navigation satellite systems (see 2.3), and the final approach will need target recognition anyway (see 2.5, 2.6).

An example of an IMS that the producer classifies as tactical grade is the ADIS16490 from Analog Devices (Analog Devices, 2022a).[6] At around $2000 price, with 100 Hz bandwidth it provides noise of the angular rate of 0.02 °/s and of the acceleration of 0.0016 m/s^2).[7] It provides 32 bits of digital output in each of the six components in a case of 47 mm · 44 mm · 14 mm, with a mass (estimated) around 60 g.[8]

A commercial-grade IMS from the same producer, ADIS16470, also with 32-bit outputs, measuring 11·15·11 mm^3 (mass around 3.5 g), has noise values at 100 Hz bandwidth of 0.08 °/s and 0.01 m/s^2, that is 4 and 6 times worse, respectively, at a price below $200 (Analog Devices, 2022c). A consumer system from Bosch, BHI260AB, with 16-bit outputs, e.g. for wrist-mounted devices or smartphones, shows similar noise values; it includes a programmable microcontroller (Bosch, 2022a). With 4.1·3.6·0.83 mm^3, that is at a mass markedly below 0.1 g and at a price of a few euros or dollars, it is much smaller, lighter and cheaper.

Again cautiously extrapolating, a tactical-grade system with specifications of the first type may fit into the size of the second; with 15 mm biggest dimension it would fit into a 20-mm fuselage/body, but not into a 10-mm one. The mass of a few grams would not present hurdles for the designers. Maybe the capabilities of systems of few millimetres size will suffice for the short flight times of missiles which would enable 10-mm bodies. Whether the requirements for tens of minutes of UAV flight could be met is unclear – maybe with a specific military development programme. This also hinges on the availability of external navigation systems, mainly global navigation satellite systems (GNSS).

5 The table contains two more grades: navigation-grade systems have positional-error rates of 2 km/h and strategic-grade ones (as used on long-range ballistic missiles) of 0.03-0.1 km/h (El-Sheimy & Youssef, 2020, Table 1). The table contains additional performance parameters of the four grades.

6 There are also ADIS16495 and ADIS16497 with variants, with slightly different specifications (e.g. Analog Devices, 2022b).

7 Root-mean-square values, calculated from the respective noise densities (in °/s/√Hz and m/s^2/√Hz, respectively) by multiplying with the square root of the bandwidth. There are several other figures of merit, e.g. bias, nonlinearity, axis misalignment. Note that some of these change with measurement range and variant. The prices are for large-quantity purchases.

8 Calculated from the volume 47·44·14 mm^3=29 cm^3 with an average density of 2 g/cm^3, gained from the ADIS16240 with a mass around 1 g and a volume of 12·12·3.6 mm^3=0.52 cm^3 (Analog Devices, 2022d, e).

2.3 Guidance Systems – Satellite Navigation Systems

Since more than 40 years global navigation satellite systems (GNSS) have been deployed, first the US Global Positioning System (GPS), later other actors launched their own constellations: Russia the Global Navigation Satellite System (GLONASS), China the BeiDou Navigation Satellite System and the European Union Galileo (others are being built up or planned). A GNSS receiver measures the propagation times of radio signals from at least four satellites of known orbits, positions and velocities to compute its location in three dimensions. For military uses the US GPS signals have additional properties that allow higher accuracy, and the US applies various export restrictions. The position accuracy can be 1 metre or below, with augmentation systems even centimetres (GPS.GOV, 2022).

An example of a military GPS receiver module for normal-size vehicles is the TruTrak-M Type II from L3Harris (USA) (L3Harris, 2021). Measuring 62 mm · 45 mm · 10 mm, the board has a mass of 38 g, power consumption is up to a few W. Markedly smaller is the MicroGRAM-M receiver from BAE Systems (USA) with 25 mm · 32 mm · 7 mm, 10 g mass and typical power consumption below 1 W (BAE Systems, 2021). GPS navigation systems have been placed on artillery shells, e.g. the Excalibur XM982 (JPEO A&A, 2017: 44-45; for another example see JPEO A&A, 2022), but here with 155 mm calibre there is no need for ultra-small receivers.

In civilian GNSS receivers strong momentum for miniaturisation has come from the internet of things and in particular from smartphones where new generations of chips have appeared in fast sequence. Accuracy improvements to the centimetre scale have come from using several GNSSs and several frequencies and incorporating additional methods and services. Sensitivity has increased markedly so that signals can be received and position tracked inside buildings (e.g. van Diggelen, 2021). One very small and light-weight system is the Multi Micro Hornet ORG1518-MK06 from OriginGPS (Israel) with size 18 mm · 18 mm · 6.4 mm and mass 8 g – this includes an antenna; typical power consumption is below 0.1 W (OriginGPS, 2019). There are smaller receiver chips with full capabilities, e.g. the Multi Nano Spider ORG4500 GPS/GNSS receiver module, also from OriginGPS, with size 4.1 mm · 4.1 mm · 2.1 mm and mass 0.1 g (OriginGPS, 2020), but here an external antenna is needed that adds size and mass.

It is notable that there are combinations of IMS and GNSS receiver, e.g. the tactical-grade VN-310E from VectorNav (USA) with additional 3-D magnetometers and two multiband GNSS receivers. The size of 31 mm · 31 mm · 12 mm, mass of 15 g and power of 1.6 W make it markedly bigger (VectorNav, 2020).

In summary, present very small civilian GNSS receiver systems with antenna can have masses of a few grams, one military system without antenna has 10 g. It is plausible that also military-grade systems including antenna with a few grams will become possible, with a size clearly below 1 cm. Thus, fitting such in a 10-mm fuselage or missile body should not present a problem. Specific efforts may be required to develop GNSS antennas on the body of such a very small missile. For aircraft with 10-mm fuselage, wings could provide a bigger space; the same holds for the area covered by (multi-)rotors.

2.4 Antennae

Here only a few general statements can be made. In the recent decades much progress has been achieved in particular with small antennas, again caused by smart phones and other wireless devices. They receive and transmit in several frequency ranges: 1.2 and 1.6 GHz for GNSS, 2.4 and 5 GHz for wireless networks. The corresponding wavelengths are: 25 cm, 19 cm, 12.5 cm and 6 cm, respectively. Thus even a quarter-wavelength antenna would be too big for a small, hand-held device, and antennas with sizes around or below one tenth of a wavelength are used. Several possibilities for their design exist, from lowering the resonance frequency to the use of metamaterials (Fujimoto & Morishita, 2014a). Optimisation has to consider various parameters, mainly input impedance, bandwidth, efficiency and gain (Fujimoto & Morishita, 2014b). One example from a military context is a circular antenna of 16 mm diameter (0.12 · wavelength) for telemetry at 2.3 GHz, mounted in the back end of a test projectile shot from a barrel (Bernard et al., 2019). This scheme would not work in a rocket-propelled missile where the back side is formed by the exhaust nozzle. A principal alternative is to use the full length of a missile for a dipole – in case of a metallic housing by introducing an insulating layer elctrically separating two parts, as done for a projectile of 30 mm diameter in (Bernard et al., 2022), in case of a non-conducting body by incorporationg metal structures. In order to avoid additional air drag by protruding parts, an antenna can also be incorporated smoothly into the curved surface of an object (conformal antenna), e.g. wrapped around a cylindrical body, as for the 61-mm-diameter fuse section of a 155-mm artillery projectile, at 2.25 GHz or 13 cm wavelength (Barton, 2020). Antenna elements might also be mounted on/in fins.

Conformal antennae can also be built from several separate elements the individual signals of which are shifted in time or phase in such a way that their superposition forms a beam in the desired direction (Josefsson & Persson, 2006). Using a conformal array antenna on a body that is small compared with the wavelength presents a significant challenge. In one example a conformal array antenna could be mounted on a truncated cone with a base diameter of 25 mm, but for 14 GHz corresponding to 2.1 cm wavelength, to be used in a proximity fuse, that is for very short range (Cong et al., 2017).

In case of UAVs with extended wings or rotor arms, more possibilities for mounting antenna elements exist. For general considerations on communication systems for small UAVs, including antennae, see (Michelson, 2015).

In summary it seems plausible that antennae could provide sufficient communication effectiveness for missiles down to 20 mm diameter, maybe even lower, maybe requiring change to shorter wavelengths. This may profit from the fifth- (5G) and sixth-generation (6G) mobile-system developments where wavelengths of millimetres and below are to be used. For UAVs, sizes (wingspans, lengths, overall rotor diameters) down to 0.1 m may be possible even without shorter wavelengths.

2.5 Cameras and Laser Radar

As with microelectronics in general, the miniaturisation of cameras has profited immensely from the advances in mobile and in particular smart phones. Various additional features are provided often, among them autofocus, electronic or optical image stabilisation and digital or optical zoom. Such video and photo camera modules with very high resolution exist with e.g. 12 million pixels at sensor formats (diameters) of 9.9 mm and at 48 million pixels at 12.7 mm (1/2.56 and 1/2.0 inch, respectively (Samsung, 2022)). In smart phones sophisticated optics are used not extending the housing thickness of several millimetres; for tele-lenses with longer focal lengths a folded optical path with a reflecting prism can be used (Samsung, 2022). Such folding would not be needed in forward-looking cameras of small UAVs and missiles. For very small body/missile diameters the electronics may have to be built behind the sensor. With lower resolution much smaller cameras are available, e.g. the NanEyeC Miniature Camera Module with 320·320=102,400 pixels, available in colour or black/white versions, measuring 1 mm · 1 mm · 2.4 mm; power consumption is 12 mW (ams, 2022). Masses of camera modules were not found, but judging from the volume (a few cm^3 in the first, a few mm^3 in the second case) they should be grams and milligrams, respectively.

In UAV/missile cameras one may also be interested in the distances to the image objects. For this purpose laser radar (lidar) can be used; in the civilian realm, much development is occurring for autonomous driving. For longer distances (up to hundreds of metres) a narrow laser beam is scanned in two angular dimensions by movable mirrors, the reflex arrival time in the respective direction is measured. Miniaturisation is possible by microelectromechanical systems technology (Yoo et al., 2018); one such double-mirror system measures 5 mm · 6 mm · 3 mm at a mass of 20 mg (Wang et al., 2020). For shorter distances (metres to few tens of metres) a faster and conceptually simpler alternative uses a widened laser beam that illuminates the full scene at once. An array of time-sensitive sensors measures the reflex arrival times or phases at each pixel, e.g. with 1024·1024 pixels on a 5 mm · 10 mm die (Analog Devices, 2020). Thus a three-dimensional scene description is available very fast. While this is acceptable in smartphones, the range may be insufficient for UAVs and missiles.

Summarising, cameras and laser radar systems can be small enough to be used on missiles down to 10 mm diameter already at present, if one accepts lower requirements even below. Similarly, they could enable UAVs of a few cm size. Whether armed forces would be interested in even smaller systems, with extremely small effects, is unclear; at least cameras are not the limiting factor.

2.6 Radar

Radar can provide not only a two-dimensional image, but also the distance to the objects in a scene. Being an active system, radars for considerable distances need relatively large antennae for a narrow beam and relatively high electric power, both not feasible on small UAVs and missiles. Radar is mainly used for bigger missiles (and projectiles) for the terminal approach, but in many cases other methods (such as semi-active radar or semi-active laser guidance) are preferred, while echoes from a transmitter on board are only used for the fuse, that is over very small (metres) distance. However, a very small experimental missile from our database (Altmann & Suter 2022a, b), the Lockhheed Martin Miniature Hit-to-Kill interceptor with 40 mm diameter, is at first guided to the vicinity of the target by a big ground-station radar, but then a small radar on board takes over; it is unclear at what range this begins.

Scaling this principle down to 20 mm or even 10 mm diameter may meet difficulties. For the same wavelength, the beam width (angle) scales with the inverse antenna diameter while for the same volume fraction the battery energy scales with the inverse of the missile size cubed. The first effect could be compensated by a smaller wavelength.[9] However, if one wants to steer the beam, several partial antennae have to be mounted beside each other, with mutual distance of the order of the wavelength. Much development is occurring in the field of driver assistance and autonomous driving. A state-of-the art fifth-generation millimetre-wave radar, the Bosch Front Radar, works at 76-77 GHz frequency, that is 4 mm wavelength (Waldschmidt et al. 2021, Bosch 2022b). The three transmit and four receive antennae cover a diagonal of about 60 mm on the printed-circuit board, achieving a detection range of 210 m. A much smaller single-chip millimetre-wave sensor with 15 mm · 15 mm size and correspondingly wider beam is recommended for ultra-short range such as car-door opening, with a maximum range of 30-60 m (Texas Instruments 2021, 2022a, b).

Thus, for around 200 m detection range a missile of about 60 mm diameter seems needed; such a range appears not achievable for much smaller missiles or UAV bodies, and radar is unlikely to be built into them (fuses for the immediate vicinity are a different matter). Whether much shorter wavelengths will become accessible[10] and whether the effort for such radar systems will appear justified for the military, is unclear.

2.7 Materials and Production

For large and small UAVs various materials have been used, among them plastics, fibre composites and metals (Gundlach, 2012: section 7.3). For insect-like UAVs, special techniques have been applied (e.g. Chen & Zhang, 2019). Here no drastic changes are expected; sizes down to millimetres have been possible since years.

As to missiles, the rocket-motor casing is subject to the highest stresses, having to withstand the pressure from the burn chamber. Often it serves as a structural element of the missile body. In existing missiles, casings are built from various types of high-strength metal alloys; in many modern types fibre composites lead to reduced weight, with glass, aramid and carbon fibres; metal-composite combinations are used, too (Chase & Thorp, 1996; Sutton & Biblarz, 2010: chapter 15). No hint was found that much stronger casing materials (such as composites with carbon-nanotubes) could arrive in the next years.

9 The half beam angle in radians is roughly given by the antenna diameter divided by the wavelength. π rad = 3.14 rad = 180º.

10 Below 0.5 mm atmospheric attenuation can present a problem (Reedy & Ewell, 1981: 38).

Additive manufacturing (often called 3-D printing), a technology that has seen massive advances in the recent decade, produces components as well as full systems by building them up layer by layer, with various applications for UAVs and aerospace in general (Goh et al., 2017; Najmon et al., 2019; Fu et al., 2022). Many types of materials can be processed by several methods. Various types of plastics can be used for small parts as well as complete bodies. Long fibres can be included to form composites. For structural components or hot or chemically aggressive environments, such as in combustion engines, various metals can be processed; processing of solid-rocket fuel is being investigated. Different materials can be combined. Additive manufacturing saves material and provides much flexibility creating complex shapes. Inner cavities can be produced easily, such as a honeycomb structure within a wing. This technology allows very small products and thus poses virtually no lower limit on the size of UAVs, see the research for insect-size UAVs (examples in Pilch et al., 2021a, b).

In missiles, a lower bound for the diameter may follow from the needed strength of the motor casing to stand the internal pressures, requiring a certain minimum thickness; an additional heat-insulating layer may be needed. If the total thickness is, say, 0.5-1 mm, then for a 10-mm missile the inner volume for fuel would reduce by 10-19%.[11] For 20 mm outer diameter the reduction would be negligible. These arguments hold independently of the method of production.

Since several years much research is being done on origami-like production of very small aircraft, in particular insect-like ones (very small robots for movement on or in other media are also being investigated). Here, a two-dimensional pattern is produced, e.g. by laser cutting a sheet or by additive manufacturing, often involving different materials e.g. for flexible joints. Then the pattern is folded to form a three-dimensional structure, sometimes actively by embedded actuators (Peraza-Hernandez et al., 2014). Often the designs are bio-inspired, some in quadcopters, others in wings (e.g. Mintchev et al., 2018; Baek et al., 2022).

Origami-like production of UAVs and components has mainly been done for sizes of centimetres or tens of centimetres. With the latter, payloads of several 100 grams are feasible, with the corresponding destructive potential. Concerning miniaturisation, small-insect-size UAVs are principally possible, but the required battery weight may present a problem, and the payload will be very small; military action would be effective only against unprotected persons. Whether mass use in swarms would change this assessment is unclear.

Additive manufacturing at present is useful mainly for prototypes and small series. If mass production will become available and cost-efficient, it – maybe together with folding techniques – can allow UAV swarms with very high numbers of elements. The Perdix unarmed UAV that formed a swarm of 103 elements in a US demonstration of 2016 had been produced via additive manufacturing (US SCO, 2017).

In summary, existing and new production methods will be further improved. They allow armed UAVs even below 1 centimetre size, but with very little destructive effect. Concerning missiles, diameters down to 20 millimetres should be feasible, below there may be problems with the fuel volume. Going beyond research and prototypes, developing milita-

11 The relative reduction of the cross-section area is $(\text{radius}^2 - (\text{radius-thickness})^2) / \text{radius}^2$.

rily useful systems of such small sizes, would require considerable efforts; whether armed forces will be motivated enough to spend such resources is unclear.

2.8 Energy Supply and Propulsion

The vast majority of small and very small UAVs are propeller-driven with the energy coming from an electrical battery (Pilch et al., 2021a: 22). This trend will likely continue. Driven by demands from portable electronics and electric vehicles and supported by state programs, lithium batteries have turned out the kinds with the highest specific energies. For lithium-ion batteries this value has increased from 90 Wh/kg in 1991 to nearly 300 Wh/kg in 2019, close to the limit of chemistry and physics (Warner, 2019: 4-5, 253-254). Markedly higher energy density is promised by lithium-metal batteries and by solid-state electrolytes, a large consortium in the US aims for 500 Wh/kg (e.g. Chen et al., 2020; Boaretto et al., 2021). For the same battery mass, a doubling of capacity would mean a doubling of range and endurance; alternatively the battery mass could be halved allowing increased payload. A few types of centimetre-size UAVs with batteries exist already (several with flapping wings) (Pilch et al., 2021a, b); a doubled battery capacity will not introduce marked change. Ultra-small UAVs with masses of milligrams will likely continue to remain confined to the laboratory.

Energy harvesting from the environment provides only extremely little energy usable for sensors, internet-of-things applications, in aerospace for auxiliary systems (e.g. Liu et al., 2021), but propulsion of militarily useful armed UAVs needs much higher energy.

Concerning other energy sources, fuel cells were used only once in a research project of 2003, the AV Hornet (Pilch et al., 2021a, b; AV, 2022a); their use in the next decade is not very likely (except if research and development for their use in cars will be strongly accelerated).

Combustion engines are used in 9 of 129 UAVs in our database, mostly for bigger aircraft. Reciprocating, Wankel as well as various gas-turbine engines are mature technologies, marked improvement is improbable. Small turbojet engines for expendable missiles or not small UAVs are being offered down to e.g. 11 cm diameter and 3.9 kg mass (the TDI-J45 (TDI, 2022)). But there are smaller jet engines for model aircraft (e.g. the JetCat P20-SX with 60 mm diameter and 350 g mass (JetCat, 2022)). Reciprocating engines can have similar size, but be lighter, e.g. the one-cylinder O.S. Engines MAX-15LA with biggest dimension 90 mm and 138 g mass (without muffler) (O.S. Engines, 2022). Thus, in case armed forces want combustion engines instead of electrical motors and devote the needed resources to their development, small UAVs (with fixed or rotary wings) down to maybe 2 cm size could be equipped with them.

There is research for a new concept of propelling small (kilogram-scale) UAVs much faster than possible with propellers, with velocities around the speed of sound (at low altitude 343 m/s = 1,235 km/h). For this, a special solid-propellant rocket motor would burn much more slowly than usually, at correspondingly lower thrust, with a longer burn time of 1-3 minutes (Vernacchia et al., 2022). Whether this idea will be seen as relevant by armed forces is unclear; development may take five or more years.

In missiles the sensors and electronics usually are powered by batteries. Higher specific energy will allow some size reduction, but since the volume scales with the third power of size, a factor of 1/2 in battery mass may translate into a size reduction by 1/1.3 only. Since even miniaturised sensors and electronics will need some energy – active communication or radar even more –, there may be a limit on downscaling of missiles, maybe at a few millimetres. In traditional missiles, control actuators with higher energy demand are often powered by so-called thermal batteries (Fleeman, 2006: 191). Whether such would be needed also for small and very small missiles is unclear. In principle, centimetre-size types are available, but the smaller ones tend to function for less than 10 seconds (Guidotti & Masset, 2006).

Regarding missile propulsion, solid propellants are well established, the energy released is already at 95% and above of the theoretical maximum, and missile designers can choose according to the respective goals (Sutton & Biblarz, 2010: Chs. 2, 13). Reducing the size of metal fuel components to nanoparticles can increase the burn rate significantly which may be relevant for some purposes, but does not change the energy (e.g. Yan et al., 2019). Also the technologies of the other missile components, e.g. the nozzle, are mature. Thus for small and very small missiles no drastic change is expected.

2.9 Swarms and Swarm Control

Swarming of UAVs is an area of active military research and development.[12] Most demonstrations and tests use small and very small UAVs, but bigger ones could be used, too. In the US military, swarming is seen as a key technology (e.g. US DoD, 2018: 34). In 2016 a swarm of 103 Perdix UAVs (unarmed, wingspan 0.30 m, made by additive manufacturing) demonstrated collective decision-making, adaptive formation flying, and self-healing (US SCO, 2017). In September 2022 attack and defence were tested using 40 armed quadcopter UAVs (Rogoway, 2022). China conducted tests with 67 and 119 fixed-wing UAVs in 2017 (Kania, 2017: 22f.). In September 2020 it tested the launch of 48 armed UAVs (loitering munitions) from a launch-tube box on a truck (Trevithick, 2020). Russia used a swarm of armed UAVs for the first time in an exercise in 2020 (Hambling, 2020). In its war against Ukraine, it has sent salvoes of dozens of armed UAVs against infrastructure targets (e.g. Stern, 2022), probably without co-ordination within the swarm.

Simple swarm attack against sites with known co-ordinates or using some ways of recognition of static targets is possible already today. Detecting mobile targets puts much higher requirements, even if international humanitarian law is neglected. Sophisticated swarm co-ordination, reaction to changes and in particular to enemy actions raise the bar even higher. Finding algorithm solutions can take many years, but incremental advances will likely occur with experiences made in testing. Thus swarms of armed small and very small UAVs are expected to move from development to deployment and use in the coming years. But the extent will depend on the possibilities of cheap mass production which in turn will hinge on the military resources devoted to such a goal. Software may remain a major bottleneck.

12 Due to their short flight time swarming does not make much sense for missiles – here one would rather speak of salvoes (Altmann & Suter 2022a: 24).

2.10 Downscaling of (armed) UAVs?

In order to assess a minimum size for an armed UAV, one can look at the smallest systems in our UAV database (Pilch, 2021a, b). The smallest rotary-wing type is the Black Hornet PRS; with a traditional helicopter design it has 12.3 cm rotor diameter, 16.8 cm length and a mass of 33 g, carrying several cameras and radio communication, with 25 minutes endurance and 2 km radio range, in service with many armed forces (Teledyne FLIR, 2022). If a weapon were to be added, its mass must not exceed a few grams. What could be achieved in principle can be seen from the slightly smaller civilian, open-source project Crazyflie 2.1, a quadcopter of 9 cm overall diameter, with flight time 7 minutes and 1 km radio range, that allows a payload of 15 g (bitcraze, 2021, 2022). The three most light-weight fixed-wing/ flying-wing research types in the database have around 200 g mass and 37 cm wingspan (Hornet, Wasp, MITE 2), the Perdix with a smalller wingspan of 30 cm needs tandem wings to carry its mass of 290 g (Pilch et al. 2021a, b). For smaller winged UAVs flapping is preferred. Here masses far below 1 gram have been demonstrated in research. A 3-gram type (DelFly Micro) carries 0.6 g of camera and communication (Delft University of Technology, 2022). The heaviest flapping-wing type (ASN-211) has 220 g mass and 60 cm wingspan, carrying a camera (EveryChina, 2022). Flapping-wing UAVs are rather fragile; whether a militarily useful armed type can come about in the next decade is unclear. The insect-size UAV attacking a person by an unspecified effect in a video animation (US AFRL, 2009) seems to not have materialised yet.

In our UAV database there are 20 armed systems, all in the “small” category (size between 20 cm and 2 m). For the 10 of these for which the maximum take-off mass and the weapon payload were found, the former ranges from 1.8 to 15 kg, the latter from 0.2 to 2.5 kg. The payload portion is between 11 and 31% with an average of 19% (Pilch et al., 2021a: 47f.). Such a range will probably hold for “very small” armed UAVs (below 20 cm size), too.

Due to the miniaturisation of components and subsystems, armed UAVs down to centimetre sizes are possible. Battery requirements for radio communication could limit downscaling but could be circumvented by autonomy. In any case the total mass as well as the payload will get very small; for the same configuration, both scale with the inverse third power of a characteristic length. Destructive payloads of grams and below may not be very attractive for armed forces with the possible exceptions of special operations (and principally of chemical/biological agents, prohibited by the respective conventions).

2.11 Downscaling of Missiles

From the miniaturisation of components and sub-systems discussed in sections 2.1 (Electronics) through 2.5 (Cameras and Laser Radar) there seems to be no clear lower limit on missile size. But such limits could ensue with Radar (2.6) – however this is dispensable – and in the areas Materials and Production (2.7) as well as Energy Supply and Propulsion (2.8).

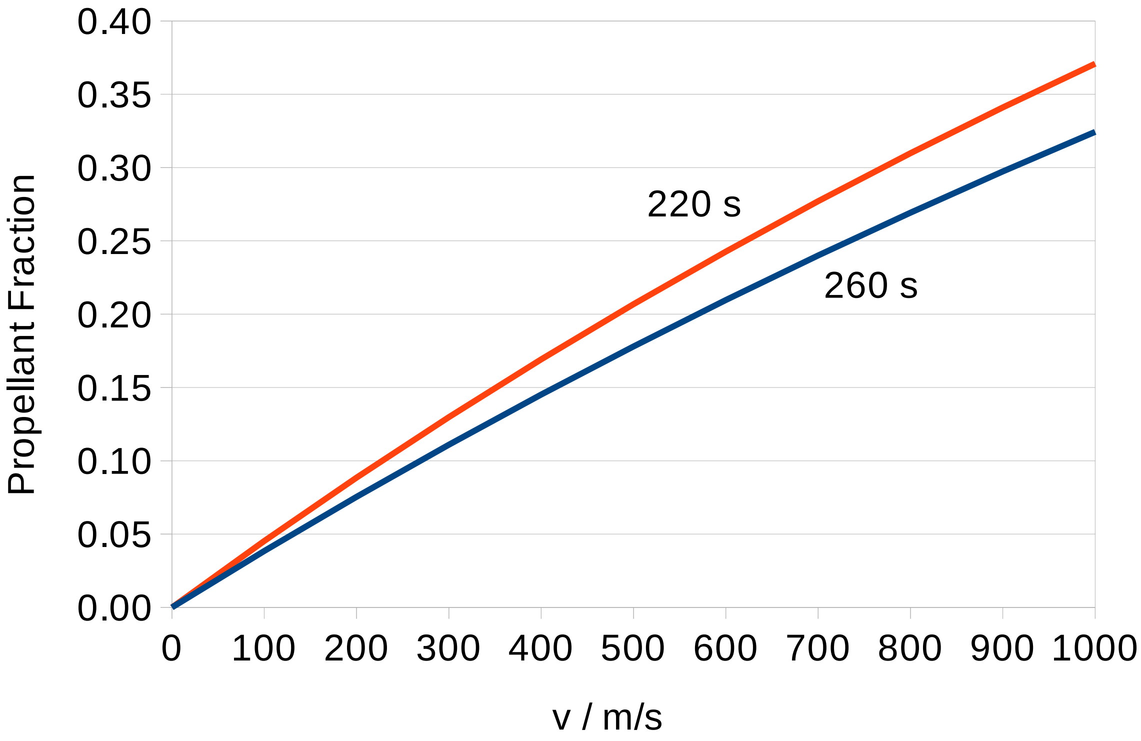

Figure 2.1 Mass fraction of propellant in the total launch mass versus the velocity to be achieved, for two values of the specific impulse I_{sp}. The gas-exhaust velocity is 9.81 m/s^2 · I_{sp}, that is 2.16 and 2.55 km/s, respectively.

This section considers more general limits on the mass and payload of missiles with rocket propulsion.[13] In our missile database (Pilch et al., 2021a, b), the burnout speeds vary between 98 and 673 m/s (much below the speeds of ballistic missiles needed for hundreds or thousands of kilometres, 2-6 km/s); smaller types generally achieve a lower speed. An estimate of the fraction of the propellant mass m_{prop} in the launch mass m_{launch} of a rocket can be gained from the needed speed increment v and the specific impulse I_{sp} by

$$\frac{m_{prop}}{m_{launch}} = 1 - \exp\left(-\frac{v}{g\,I_{sp}}\right) \qquad (2.1)$$

where g = 9.81 m/s^2 is the earth gravity acceleration at zero altitude and g · I_{sp} is the exhaust velocity of the burn gases.[14] The equation assumes launch at zero speed and the thrust force much higher than the drag force. The specific impulse of tactical ballistic missiles is between 220 and 260 s (Fleeman, 2006: 132ff.; Sutton & Biblarz, 2010: 495ff.), corresponding to exhaust velocities between 2.16 and 2.55 km/s. As Figure 2.1 shows, for velocities

13 Turbojet engines are rarely used for small missiles and present higher hurdles for miniaturisation, see section 2.8.

14 Inversion of $\Delta v = -g\,I_{sp} \ln\left(1 - \frac{m_{prop}}{m_{launch}}\right)$ (Fleeman, 2006: 122).

from 100 to 700 m/s the propellant fraction is relatively low, from 5 to 30%. This does not put a lower limit on the size of a (very) small missile. For existing tactical missiles of many sizes, the inert mass (that is, launch mass minus propellant mass minus payload mass) is about 20% of the launch mass (Fleeman, 2006: 144, 175); this probably holds for small and very small missiles, too. Subtracting 5-30% and 20% from the launch mass leaves 75-50% for the payload.[15]

In order to estimate the absolute payload for missiles even smaller than 40 mm, one can use average values of the length-to-diameter ratio and of the overall density. For tactical missiles typically the former is between 5 and 25 (Fleeman, 2006: 22). The latter is 1.4 g/cm^3 for missiles of very many sizes (48 types from 9 kg to 4,100 kg mass, assuming cylindrical bodies, Fleeman, 2006: 145). For the nine missile types in our database with diameters below 51 mm for which length, diameter and launch mass had been found (diameters from 37 to 44 mm), the density was similarly computed from the volume V of a cylinder of equal length l and diameter d – this neglection of the tapering tip should not produce a big error. This density is

$$\rho = m / V = m / (\pi \, l \, (d^2 / 4)) \,. \qquad (2.2)$$

If the nominal length-to-diameter ratio $(l/d)_{\mathrm{nom}}$ is given, the length is equal to the diameter times this ratio, thus the volume is

$$V = \pi \, (l / d)_{nom} \, (d^3 / 4) \,. \qquad (2.3)$$

Table 1 shows the minimum, average and maximum values of the length-to-diameter ratio and the density. With 2.1 g/cm^3 the average density of these small and very small missiles is clearly higher than the average over many bigger missiles. Figure 2.2 shows how the calculated missile mass depends on the missile diameter for the extreme cases that both parameters are at their respective minimum or maximum, and at the average values.

Table 1 Minimum, average and maximum values of length-to-diameter ratio and density of the nine missiles with diameters below 51 mm in our database for which these values could be determined.

Parameter	Minimum	Average	Maximum
Length-to-diameter ratio l/d	10.0	15.1	22.8
Density ρ/(g/cm^3)	1.43	2.09	3.21

It is evident that the mass of a 20-mm-diameter missile would be much below 1 kg and that of a 10-mm one below 100 g, with the payload 50-75% of this or less, in any case providing a very small destructive capability.

This approach assumes that all missile components scale in the same way. However, as noted above, if a motor casing needs a certain material thickness, the relative size of the fuel volume will decrease. This effect could put a lower practical limit on the missile diameter – maybe around 10 mm.

15 Such downscaling may no longer hold if the burn-chamber casing needs a certain thickness, see section 2.7. In this case the payload fraction would be smaller.

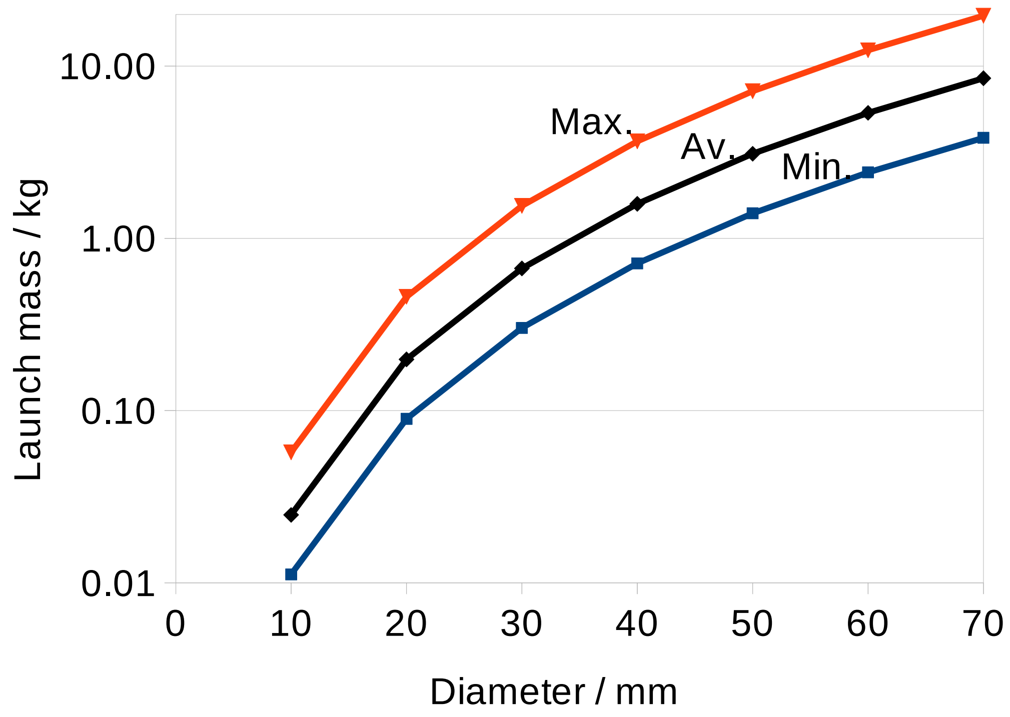

Figure 2.2 Cylindrical-missile mass versus diameter for minimum, average and maximum values of length-to-diameter ratio and overall density, mass axis logarithmic.

2.12 Conclusion on Technological Trends

It is obvious that various technologies relevant for small and very small armed UAVs and missiles are evolving fast and will advance further, in many areas supported by commercial developments in portable devices and for autonomous driving. The armed UAVs and missiles that exist already or are in development provide relevant military capabilities. Smaller types, down to sizes of centimetres and even below are possible in principle, but at much reduced destructive potential. Compensation may be possible by their use in (large) swarms.

3 Preventive-Arms-Control Considerations

This chapter explains the concept of preventive arms control and applies it to small armed UAVs and missiles. But at first the role of such systems in recent wars is covered.

3.1 Small and Very Small Armed UAVs and Missiles in Recent and On-going Wars

In recent and on-going wars armed UAVs and missiles have played and are playing a strongly increasing role, however the great majority of these systems have been and are bigger than our "small" category (UAV size up to 2 m, missile diameter below 69 mm, Pilch et al. 2021a; Altmann & Suter, 2022a). But there are a few notable exceptions.

In the *Libyan civil* war in 2020 the armed quadcopter Kargu-2 from STM (Turkey), overall diameter 0.78 m, was used as a loitering munition to attack logistics convoys and retreating forces (UN Panel of Experts, 2021: 17). Whether the attacks were remotely controlled by a human or the autonomous-attack function of the UAV was used, is not fully clear (Kallenborn, 2021). Small or very small missiles seem to not have been used.

In *Russia's war against Ukraine*, until January 2023 Ukraine received "over 700" Switchblade and "[a]pproximately 1,800" Phoenix Ghost "Tactical Unmanned Aerial Systems" (loitering munitions) (US DoD, 2023) (wingspans Switchblade 300: 0.69 m (AV, 2022a), Switchblade 600: about 1.8 m,[16] Phoenix Ghost: size unknown, but generally similar to Switchblade (Copp, 2021)). Already before the war, Ukraine had indigeneous small armed UAVs (e.g. the Athlon ST-35 loitering munition (around 1 m wingspan)[17] and the Matrix-UAV Comandor (1.5 m overall diameter), and had imported WB Electronics Warmate UAVs (1.4 m wingspan) from Poland (Pilch et al., 2021a, b). In the war, many Ukrainian actors have converted small commercial photo multicopters to weapons, e.g. dropping small explosive charges; here, the hobby Mavic and professional Matrice quadcopters from the Chinese firm DJI (diagonal length 0.38 and 0.67 m, respectively (DJI 2023a, b)) are playing a prominent role; Russian actors have tried to do the same (Greenwood, 2022a, b, c, d).

Russia, in the first months of the war, used KYB-UAV systems from Zala (1.2 m wingspan) (ZALA, 2022), later also Zala Lancet (around 1 m wingspan)[18] (Chang, 2022). The armed UAVs imported in high numbers later in 2022 from Iran, maybe modified (HESA Shahed-136 or Geran-2) (Eslami, 2022), with 2.5 m wingspan are above our "small"-UAV limit.

Defensive measures used against small UAV include electronic countermeasures (Zabrodskyi et al., 2022: 33, 37) and small quadcopters smashing into the target or throwing nets (e.g. Hambling, 2022; Fortemtech, 2022).

Even though the effect of a single small armed UAV is limited, in high numbers they can cause significant damage to military as well as civilian targets. This holds for types devel-

16 Estimated from photo in (Valpolini, 2020).

17 Estimated from photos in (Athlon Avia, 2022).

18 Estimated from photos in (Chang, 2022).

oped for the military, but also for converted commercial UAVs. Both are seen as important enough to try to defend against them.

Of the missiles used for various purposes by both sides, virtually all seem to be of traditional diameters, in man-portable air defence systems (MANPADS) e.g. for Ukraine Igla-1 of Soviet origin (72 mm) (Zabrodskyi et al., 2022: 20) or Stinger (70 mm) transferred by the USA (US DoD, 2023), for Russia Verba (72 mm) (Kadam, 2022); other missiles are much bigger. None in our "small" class (diameter below 69 mm) were found, thus small and very small missiles have not been used in this war either.

3.2 Overview of Preventive Arms Control[19]

While usual arms control prohibits or limits weapons (sometimes also personnel) that exist already and have been deployed, preventive arms control applies bans or limitations to new military technologies or new military systems before they are acquired or deployed. In the somewhat idealised sequence how new military technologies and systems come into existence, are used and finally removed – research, development, testing, production/acquisition/deployment, use, and disposal – preventive arms control acts before the final three stages, affecting at least acquisition and deployment.[20] In order to be comprehensive and avoid misperceptions and mistrust, often already the stages of development and testing are included. Research, on the other hand, usually is not limited directly, because on the one hand the outcome cannot be predicted, and on the other hand the results may be used in different areas. An additional reason is that verification in laboratories, offices and computers would have to be extremely intrusive and costly.[21] Several arms-control treaties contain preventive elements, directly or indirectly, from the Antarctica Treaty (1959) via the Anti-Ballistic Missile Treaty (1972) and the Chemical Weapons Convention (1993) to the Comprehensive Nuclear-Test-Ban Treaty (1996).

Preventive arms control needs to be prepared conceptually in interdisciplinary research in four steps: 1. Prospective scientific analysis of the technology in question. 2. Prospective analysis of the military-operational aspects. 3. Assessment of both under the criteria of preventive arms control. 4. If a negative outcome has to be feared, then devising options for limitation and for verification of compliance with them. Ideally, states would take the results and start corresponding negotiations.

In principle, applying limits early, before armed forces feel dependent on the new technology, should be easier. However, when there are no actual experiences yet and negative

19 For detailed presentations see (Altmann, 2006: chapter 5; 2008).

20 There is a case where acquisition and deployment are not prohibited while use is, namely in the Protocol on Blinding Laser Weapons of the Convention on Certain Conventional Weapons (CCW) (CCW, 1995). But the effect was that no such weapons were acquired or deployed, and that even research, development and testing were ended. Only work for dazzling has continued, avoiding permanent blindness.

21 There is one exception: The Comprehensive Nuclear Test Ban Treaty, banning all nuclear explosions, implicitly excludes research under such conditions, and the events are so big that global monitoring of seismic, infrasound and hydroacoustic signals and radioisotope concentrations suffices for verification, augmented by on-site inspections (CTBTO, 2023).

outcomes have not yet been seen in reality, political decisions may be difficult to achieve. Another problem is that armed forces will be interested in new options for combat, resisting efforts for preventive limitations. Additional opposition may come from the armament industry.

A list of criteria for preventive arms control was developed in joint projects in Germany (Neuneck & Mölling, 2001). The criteria are put in three groups:

I. Adherence to and further development of effective arms control, disarmament and international law
   - Prevent dangers to existing or intended arms-control and disarmament treaties
   - Observe existing norms of humanitarian law
   - No usability for weapons of mass destruction

II. Maintain and improve stability
   - Prevent destabilisation of the military situation
   - Prevent technological arms race
   - Prevent horizontal or vertical proliferation/diffusion of military-relevant technologies, substances or knowledge

III. Protect humans, environment and society
   - Prevent dangers to humans
   - Prevent danger to environment and sustainable development
   - Prevent dangers to the development of societal and political systems
   - Prevent dangers to the societal infrastructure.

While groups I and II hold for war and its prevention, group III applies mainly to peace-time military uses of technologies or systems.

3.3 Assessment under the Criteria of Preventive Arms Control[22]

Applying the criteria to small and very small armed aircraft and missiles systematically leads to the following statements.[23]

Criteria Group I

Dangers to arms control and disarmament could follow from small and very small UAVs or missiles in a few specific ways. Because they are too small for nuclear weapons, nuclear arms control is not relevant. The prohibitions of chemical and biological weapons are general, independent of the size of carriers. Smaller UAVs or missiles could bring new options for carrying chemical or biological agents, but as long as the respective conventions are being complied with, no danger for them will ensue.

22 For a corresponding discussion of armed uninhabited vehicles in general, see (Altmann 2013, 2020).

23 The focus is on armed UAVs since these produce the biggest problems; small and very small UAVs for surveillance and other information/communication purposes need a separate discussion. They can be used in attacks, e.g. for artillery targeting. A special dual-use problem is that many types are commercially available, some even to be assembled from parts.

In the conventional realm, the Treaty on Conventional Forces in Europe (CFE Treaty), (1990, with unratified adaptation 1999) is relevant (CFE, 1990, 1999). It is out of function with the most important Eastern partner, Russia, since it suspended its participation in 2007 and halted it completely in 2015. But the Treaty has continued to function with the other parties, including Belarus and Ukraine, until 2021 at least (US DoS, 2022). A problem arises with the definitions of treaty-limited items in Article II (that do not mention a crew on board, so that they hold for uninhabited systems as well): While the definitions of a “battle tank” and of a "heavy armament combat vehicle" contain lower mass limits (16.5 and 6.0 metric tonnes, respectively), the ones of "combat aircraft" and "combat helicopter" hold independently of their mass so that arbitrarily small armed fixed/variable-wing or rotary-wing UAVs are covered by them, and their number would count against the treaty limits for the traditional, big combat aircraft and helicopters. Armed forces are unlikely to accept this, so the introduction in significant numbers into Europe would endanger the Treaty or a possible follow-on agreement, unless the definitions and limits were modified.

Missiles are not covered by the Treaty, neither big ones nor small ones.

A definition problem exists also in the United Nations Register of Conventional Arms (UN ROCA, 2023a, b), a transparency- and confidence-building measure covering exports and imports. Here the definition of “Combat aircraft and unmanned combat aerial vehicles (UCAV)” (Category IV) differentiates between crewed and uncrewed systems whereas the one of “Attack helicopters” (Category V) puts both in one basket. These definitions do not give a mass limit so that transfers of small and very small armed UAVs are legally included and should be reported in the same manner as the bigger ones.

Concerning missiles, there is a Category VII “Missiles/missile launchers” covering “Guided or unguided rockets, ballistic or cruise missiles capable of delivering a warhead or weapon of destruction to a range of at least 25 kilometres”. This minimum range excludes all missiles of our database. But the definition also includes “remotely piloted vehicles with the characteristics for missiles as defined above but does not include ground-to-air missiles”; autonomous vehicles are not (yet) included. Of the 13 UAVs in our database that have ranges above 25 km one type (Comandor, 1.5 m size) can be armed, so that its transfers would have to be reported. The definition also contains “Man-portable air defence systems (MANPADS)”. The existing types have diameters from 69 mm up, but our database includes several surface-to-air missiles below this; if these are to function as MANPADS, their transfers would have to be reported as well. If done, there would be no danger to the Register. In light weapons on which states can additionally report, some categories of small and very small missiles are covered by “4. Recoilless rifles” and “5. Portable anti-tank missile launchers and rocket systems” – without explicit definitions, thus independent of diameter or mass.

The Arms Trade Treaty (ATT, 2022a) refers back to these definitions so similar arguments apply there.[24]

With respect to *existing norms of humanitarian law*, the issues that small and very small armed UAVs and missiles would entail are more or less similar to those of their larger

24 Note that in 2014 the standard reporting form from the UN ROCA had split the “Attack helicopters” category into manned and unmanned sub-categories, too, however in 2016 this was changed (ATT, 2022b: fn. 4).

variants, dangers arise rather from the mode of their use, if e.g. the fundamental rules of distinction, necessity or proportionality are implemented insufficiently by remote control. Violations of international humanitarian law have to be feared to a greater extent if uncrewed weapon systems would attack autonomously, again at first sight independent of size. Autonomy would be more or less required for attacks by swarms. Insofar as smaller size would likely allow cheaper and easier mass production the dangers of violations would increase. In addition, smaller vehicles will have fewer sensor and processing capabilities, so that classification of detected objects and subjects as legitimate military targets would be even less reliable.

Concerning *utility for weapons of mass destruction*, small and very small armed UAVs and missiles cannot carry nuclear weapons the mass of which is far above 100 kg; the Missile Technology Control Regime in its Category I uses 500 kg as a threshold, based on an assumed first nuclear weapon of a proliferator (MTCR, 2022a). Even the smallest "nuclear land mines" that had been developed for soldier emplacement with yields of 10 to 1,000 tons of TNT-equivalent had a mass around 30 kg (Cochran et al., 1984: 311), clearly requiring bigger carriers.

To contaminate a significant area, chemical weapons have to be dispersed in hundreds of kilograms; artillery grenades contained 3 or 6 kg agent each, bombs to 160 kg existed.[25] Some bigger types in our UAV and missile databases can carry several kilograms (one UAV even 50 kg) (Pilch et al., 2021a, b; Altmann & Suter 2022a, b), but would have to be used in high numbers. Of course use and stockpiling are prohibited by the Chemical Weapons Convention. However, non-state actors could attack single sites and produce mass casualties.

Biological weapons could affect high numbers of people even with minute quantities of agent, so that even the smallest UAV and missile types could be used as carriers. The Biological and Toxin Weapons Convention effectively blocks use by states, but non-state actors could injure and kill many people with even with very small UAVs or missiles (see Criteria Group III below).

Finally, there has been the argument that due to the massive devastation that they could create, "armed fully autonomous drone swarms" could be regarded as weapons of mass destruction themselves, possibly with thresholds for "the number of armed drones and the types and sizes of munitions" (Kallenborn, 2020). For small and very small UAVs with correspondingly smaller destructive potential, the number would have to be accordingly higher.

Criteria Group II

Destabilisation of the military situation between potential enemies, that is increased pressure to attack or react fast in a strong crisis, can result from the existence of armed UAVs in general, because of a lower threshold for applying force because one's own troops are outside of the combat zone, or in case of autonomous weapons due to inadvertent escalation caused by errors or misperceptions, leading to uncontrolled interactions (Altmann & Sauer, 2017). Missiles can destabilise mainly if they can carry nuclear weapons over long range. Small and very small UAVs and missiles have limited range and limited payload and thus provide limited potential for deep penetration, so not much destabilisation on the strategic level is to be expected. Mutual interactions between fleets of autonomous small and very

25 Computed from numbers of munitions and quantities of agent in (US Army, 1997).

small UAVs may occur, but likely would not lead to high-level escalation; such danger would rather ensue from the various other, mostly bigger UAVs and missiles. However, smaller systems are more difficult to detect and to defend against, and surprise attacks against a small country or a region close to the border are conceivable.

A problem may arise with attacks against nuclear-strategic installations, foreseen for precision-guided bigger cruise missiles (technically UAVs) and missiles (Miasnikov, 2009). They could be replaced by swarms or salvoes of small and very small UAVs or missiles, respectively, carried to the vicinity of the target by larger aircraft or missiles.

A *technological arms race* usually unfolds whenever a new technology promising increased combat strength comes into view and is being developed with high effort by potential adversaries. Such a race is already on since more than two decades in bigger armed UAVs and defence against them, in normal-size missiles and missile defence development is proceeding steadily since a longer time. For autonomous weapon systems – independent of size – some virtual race is happening in research, development and testing, fuelled by high expectations in military utility. But systematic deployment has not begun,[26] maybe because of high requirements on IHL compliance; some state restraint may also have to do with the on-going governmental-expert discussions in the context of the Convention on Certain Conventional Weapons (CCW) (UNODA, 2023a).

In small and very small UAVs a technological arms race has only just begun, accelerated by the Russian war against Ukraine (see section 3.1). Further acceleration, also in the direction of autonomous attack and swarming, is probable if no limiting measures will be introduced. In small and very small missiles, on the other hand, some research and development are underway, but it seems that armed forces do not put much emphasis on them at present – normal-size missiles are quite effective. A technological arms race may ensue if a strong military power will proceed decisively.

Horizontal and vertical proliferation have been a concern with bigger armed UAVs and missiles for decades. In small and very small UAVs it has begun and will likely increase, but not (yet?) in small and very small missiles. Obviously, transfers of smaller systems are easier; this holds also for covert or illicit transfers to non-state actors. If sophisticated systems that will have been developed by states will find their way into the hands of such actors, these would command much more advanced systems than they could have fabricated by themselves. Consequently, limitations among states indirectly would also limit the degree of sophistication of non-state-actor systems. Export-control regimes such as the Missile Technology Control Regime (MTCR, 2022a) or the Hague Code of Conduct against Ballistic Missile Proliferation (HCoC, 2022) have no effect on small UAVs and missiles, because they cover only big systems with sufficient payload to carry a nuclear warhead (see section 3.6).

26 In a wide, functional definition of an autonomous weapon system (AWS) also existing short-range defence systems with automatic mode count as AWS (for a differentiated approach in a possible AWS prohibition see (Sauer, 2021)). In a narrower understanding AWS would patrol in a certain area, search for potential targets, select and attack them (e.g. ICRC, 2021). One such system exists already: the loitering munition Harpy which, however, only attacks radars, not other classes of targets (IAI, 2017). On potential autonomous attacks by small UAVs in Libya 2020 see (UN Panel of Experts, 2021: 17; Kallenborn, 2021).

A proliferation risk can also arise if components of small systems can be produced by additive manufacturing. Here the required information resides in the digital control files access to and distribution of which would be easier than if specialised components would have to be transferred as such.

Criteria Group III

Dangers to humans, to social and political systems, and to the societal infrastructure can be foreseen should small or very small UAVs or missiles fall into the hands of criminals. Both kinds would be ideal tools for terrorists – selectively they could attack important persons or institutions. Mass destruction could be produced by infectious biological agents – terrorist groups having such goals would not comply with the Biological Weapons Convention.[27] Here, limitations of small and very small UAVs and missiles among states would contain dangers preventively.

Direct *dangers to the environment and sustainable development* from small and very small UAVs and missiles are not expected – except if dangerous substances e.g. from fuel would be released, but the problems would be smaller than with bigger systems.

The main finding from the criteria discussion is that small and very small UAVs and missiles raise relevant concerns, even though these are stronger with their bigger counterparts. As a consequence, arms control seems advisable; it would be preventive for many of the small and very small systems.

3.4 Options for Limitations or Prohibitions

Small and very small armed UAVs and missiles that would act as autonomous weapon systems (AWS) would best be prohibited in common with the respective bigger systems in a ban of weapons with autonomy in the critical functions of selecting and engaging targets that are not under meaningful human control.[28] Since 2014 the member states of the Convention on Certain Conventional Weapons (CCW) (CCW, 1980; UNODA, 2023b) have held informal meetings of experts, since 2017 on a more formal level as a Group of Governmental Experts, to discuss and assess “questions related to emerging technologies in the area of lethal autonomous weapons systems.” (UNODA, 2023a).[29] The debate so far has

27 A detailed technical analysis of small-UAV use by terrorists estimated that nearly 50% of the launch mass could be payload (Miasnikov, 2005). In a mathematical-modelling example 900 g of weapons-grade anthrax, released at 100 m height just upwind of a large U.S. city, 1.5 million people would become infected and 123,000 would die (Miasnikov, 2005: fn. 20, citing (Wein et al., 2003)). Another possibility would be dispersing radioactive substances; 2 kg of plutonium-239 with 50 g of Cesium-137 over San Diego would deliver radioactive doses to 12,000 people with 500 lethal (Miasnikov, 2005: fn. 21, citing (Bakanov, 2002)).

28 For early discussions and proposals see (Altmann, 2013, 2020: section 5.2). There an AWS ban was recommended with exceptions for existing short-range defence systems with an automatic mode. The present wording follows (Sauer, 2021). See also (ICRC, 2021).

29 “Lethal autonomous weapons systems” (LAWS) is the term used in this context, but the “lethal” seems overly restrictive and ambiguous. AWS could be directed not only against humans, but against military equipment (possibly with human crews inside); also, AWS could be equipped

produced eleven relatively weak guiding principles for development and use of AWS, but a mandate to negotiate limitations or a prohibition could not be agreed on due to the consensus principle used. While 30 countries have called for a legally binding ban and many more are sympathetic, fewer than 10 countries are opposed (Campaign, 2020).[30] Systematically an AWS ban would fit in the CCW as a new Protocol VI, similarly as Protocol IV of 1995 that prohibits the use of blinding laser weapons (CCW, 1995). The CCW discussions are continuing, but a consensus seems out of reach for the time being.[31] As a consequence, calls for a separate treaty, as done 1997 with the Anti-Personnel Land Mines Convention (UNODA, 2023c) and 2008 with the Convention on Cluster Munitions (UNODA, 2023d), are getting louder (e.g. Campaign, 2022).

If AWS are prohibited but remotely controlled uninhabited weapon systems remain legal, verification of compliance poses a serious problem. The usual visual confirmation of weapon properties during on-site inspections or manoeuvre observations cannot be used since the same physical system could be used in both modes. Inspection of the control software would be too intrusive to be accepted, and the algorithms could be changed after an inspection anyway. A way out is to prove after the fact that any single attack had been under the control of a responsible and accountable human. For this, all sensor and communication data and the activities of the human controller would be recorded securely by each side. Hash codes of these data would be sent to a treaty implementation organisation which could later ask for the original data, checking their authenticity with the hash codes (Gubrud & Altmann, 2013).

A comprehensive AWS ban would strongly limit the combat effectiveness of swarms, since that hinges to a large extent on the autonomous action of the swarm elements, large or small. Thus also the use of swarms for mass destruction would be excluded.

If such a blanket AWS ban will not be possible, then limits on armed swarms should be agreed upon. At a minimum the use of armed, fully autonomous UAV swarms as weapon of mass destruction (WMD) should be excluded. This could be done by limits on the numbers of elements of different sizes and combat potentials, maybe by forming a swarm score as proposed in general terms by (Kallenborn, 2020).[32]

In the interest of stability and compliance with international humanitarian law a general prohibition of armed swarms applying to air, ground, and water vehicles of all sizes would be best, but may be difficult to achieve. Qualitative and quantitative limits in particular on UAV swarms could at least contain risks. Such limits could include the number of swarm elements, their size(s), the armament(s), the range, and the capacity for transport to the target area. Here, detailed research is required, including the question how small and very small armed UAVs should count against bigger types.

with “non-lethal” weapons.

30 In October 2022 a joint statement from 70 countries was delivered to the First Commitee of the UN General Assembly calling for “appropriate rules and measures, such as principles, good practices, limitations and constraints” (UN First Committee, 2022); the countries included four out of the eight named as opposing a legal proibition in (Campaign, 2020).

31 See the CCW Reports from (Reaching Critical Will, 2022).

32 UAVs are the most problematic class here; how far swarms of armed, uncrewed ground or water vehicles could act as WMD and whether such should be limited needs additional research.

Since smaller armed UAVs and missiles would be easier transported and used covertly, proliferation to and use by non-state actors including terrorists could be prevented or at least strongly hampered by an agreement among states to not develop and acquire such systems below a certain size. A systematic approach could stipulate lower size limits according to our definitional limits for “small” armed UAVs (size up to 2 m) and missiles (diameter below 69 mm (Pilch et al., 2021a; Altmann & Suter, 2022a). However, this would mean withdrawing several small armed UAVs that exist already (our database of May 2021 contains 24 armed UAVs (with none in the “very small” class) out of 152 types (Pilch et al., 2021a: section 8.3) of which 19 were deployed/on offer (Pilch et al., 2021b). The situation is somewhat similar with missiles. The missile database of December 2021 with 50 types, all armed (Altmann & Suter, 2022a, b), contains 37 types that are deployed or on offer in the “small” class (diameter above 40 mm and below 69 mm); some are old and may no longer be in production, but several are recent.

If such size limits will not be acceptable, one could think of thresholds at our definitional limits for “very small” UAVs and missiles (size below 0.2 m and diameter up to 40 mm, respectively). For UAVs one expects no big difficulties since our database has no armed UAVs in this size class. The missile database, on the other hand, contains 8 deployed “very small” types, some of them recent. Here a prohibition may meet stronger military resistance.

If such restrictions cannot be agreed upon, a prohibition could use even smaller limits, e. g., 0.1 m and 20 mm, respectively. This would exclude insect-like armed UAVs and pencil-size missiles, but also systems of mm and even lower size, as they could become possible by nanotechnology (Altmann, 2006: section 4.1.16). However, this would not significantly limit the capabilities of non-state actors.

Because there are many more small and very small UAV types than missile types, because developments in UAVs are much more dynamic, in particular regarding the recent and on-going wars, special numerical limits on small and very small UAVs seem advisable. These could also address the problem of commercial or hobby UAVs converted to carry and release weapons.

If in some future political change will allow resuming discussions on a stable security order in Europe, armed UAVs should be included in the list of treaty-limited equipment in a possible successor to the Treaty on Conventional Armed Forces in Europe (CFE Treaty).[33] The categories and numerical limits for small and very small armed UAVs will have to vary according to configuration (fixed/rotary/flapping wings) and size or payload. Detailed research should be done on possible designs, even though the prospects for renewed conventional arms control in Europe are negative for the time being.

Research would also be useful on a possible differentiation between offensive and defensive uses of small and very small missiles – if armed forces do not want to forgo such missiles, limiting offensive uses might contribute to stability.

33 For some ideas, now far from potential implementation, see (Schmidt, 2017; Richter, 2017; Zellner et al., 2018).

3.5 Confidence- and Security-Building Measures, Transparency

Confidence- and security-building measures (CSBMs) can act as a precursor to legally binding arms control treaties, but can also underpin them. Virtually all kinds of CSBMs holding for conventional armed forces in Europe under the Vienna Document 2011 (OSCE, 2011) could be applied, mutatis mutandis, to small and very small armed UAVs and missiles, from exchange of information via demonstration of new weapon types to observation of miliitary activities.

For transparency measures in the UN framework, the definitions of the arms categories of the UN Register of Conventional Arms Transfers and of the Arms Trade Treaty should be systematised – e.g. introducing crewed/uncrewed categories beyond combat aircraft and better differentiating betweeen armed UAVs and missiles. Also some definitions should be expanded, so that small and very small armed UAVs and missiles are fully covered, without exceptions for ground-to-air missiles and without range thresholds (see section 3.3: Criteria Group I).

3.6 Export Controls

Most export control regimes are asymmetric and thus problematic: some producer countries grant themselves military systems while trying to block access by others. There is one exception: the Australia Group for chemical and biological dual-use items (Australia Group, 2023) because nearly all countries are members of the Biological Weapons Convention and of the Chemical Weapons Convention. The other regimes are useful nevertheless insofar as they limit the proliferation of dangerous technologies to non-state actors. However, they mostly cover big systems.

The *Missile Technology Control Regime* (MTCR) is about potential carriers of WMD, in particular nuclear weapons. Category I includes “complete rocket systems (including ballistic missiles, space launch vehicles and sounding rockets) and unmanned air vehicle systems (including cruise missiles systems, target and reconnaissance drones) with capabilities exceeding a 300km/500kg range/payload threshold; production facilities for such systems; and major sub-systems including rocket stages, re-entry vehicles, rocket engines, guidance systems and warhead mechanisms.” Category II, where less restraint is recommended, includes the same categories “capable of a maximum range equal to or greater than, 300km” and “a wide range of equipment, material, and technologies, most of which have uses other than for missiles capable of delivering WMD.“ (MTCR, 2022a). Nearly all small and very small UAVs and all smal and very small missiles in our databases are far below this range limit.[34] The MTCR has one case without a range limit, in Category II: UAVs with “an aerosol dispensing system/mechanism with a capacity greater than 20 litres” (MTCR 2022b: 19.A.3.). This excludes virtually all small (and all very small) UAVs of our database

34 One of 152 types, the MatrixUAV Comandor with jet engine, achieves 400 km (Pilch et al., 2021a, b).

because they cannot carry such a system.[35] Also the subsystems part of the MTCR Technical Annex focuses on items usable for missiles or UAVs above 300 km range. A meticulous reading may find instances of “Equipment, Assemblies and Components”, “Test and Production Equipment”, “Materials” or “Software” that could also be used for small missiles or UAVs, e.g. in propellants (Item 4) or composites (Item 6), but most descriptions contain “for use” or “usable” in the systems above 300 km range (MTCR 2022b). In principle, the MTCR scope could be widened to include missiles or UAVs with much lower range or payload limits, but such a drastic step seems far-fetched.

The *Hague Code of Conduct against Ballistic Missile Proliferation* (HCoC) aims “to prevent and curb the proliferation of Ballistic Missile systems capable of delivering weapons of mass destruction” (HCoC, 2012) and thus does not apply to small and very small missiles that by trajecctory and range, and thus size, do not count as ballistic (and it does not cover cruise missiles and other armed UAVs).[36] Extension to smaller, non-ballistic missiles is practically excluded as well.

In the *Wassenaar Arrangement On Export Controls for Conventional Arms and Dual-Use Goods and Technologies* the participating states undertake to regulate transfers “in order to contribute to regional and international security and stability … thus preventing destabilising accumulations” and also “the acquisition of these items by terrorists” (Wassenaar, 2022a). The Munitions List contains “rockets, […] missiles, […] specially designed for military use“ as well as “’UAVs’, Remotely Piloted Air Vehicles (RPVs), autonomous programmable vehicles” that are “specially designed or modified for military use,” all without any size, mass, or range limit (Wassenaar 2022b: para. ML4.a., ML10.c.). Thus, the participating states are encouraged to block exports of small and very small armed UAVs and missiles in some circumstances. However, accumulations by member states and technologically competent states outside of the regime are beyond the scope of the Wassenaar Arrangement, and these likely are much more destabilising.

Summarising, export control can play a role in preventing proliferation of small and very small armed UAVs and missiles to some actors, but does not limit quantitative and qualitative arms races in these systems.

35 Also here the MatrixUAV Comandor is the exception with 50 kg payload (Pilch et al., 2021a, b).

36 A ballistic missile follows a ballistic trajectory, i.e. subject only to gravity and to aerodynamic forces (while in the atmosphere) over most of its flight path, i.e. after burnout of the rocket engine. The engine throws it upward at a certain angle after which it rises and then falls down again, following an elliptical trajectory while outside of the atmosphere. The range is between many times 10 km and more than 10,000 km. See e.g. (FAS, 2000).

4 Conclusion

In many technology areas relevant for small and very small armed UAVs and missiles continuous advance is foreseen, often driven by civilian industry, in particular in the areas of portable devices and electrical and autonomous cars. Depending on the resources spent, military development can miniaturise armed UAVs and missiles further, principally down to centimetre size and smaller. This would come at the expense of much reduced destructive effect which, however, can be compensated for by improved targeting precision, expected anyway, and by high numbers which in turn could be made possible by low costs of production.

Small and very small armed UAVs and missiles present new possibilities for offence, in particular for attacks in swarms and salvoes. Under some conditions they could produce mass casualties. Destabilisation could ensue in some fields. Small weapon systems can support the tendency towards autonomous attack. Proliferation of small and very small armed UAVs is already occurring, fuelled in particular by the on-going war against Ukraine. Proliferation in missiles up to now is rather centred in traditional sizes, that is 69 mm diameter and above. Both kinds of small and very small systems could become tools for terrorism.

Even though bigger systems are more problematic, small and very small armed UAVs and missiles provide their own, specific contributions to reducing international security. To contain these risks, preventive arms control is recommended. It would be the more effective, the more comprehensive the regulations would be devised. In particular, prohibitions of and limits on weapon systems should be independent of their sizes as far as possible.

Our analysis arrives at the following recommendations. They are ranked by the degree of comprehensiveness: if one is not attainable, then the next, weaker one should be striven for. Thus, the international community should negotiate and conclude:

1. A prohibition of weapons with autonomy in attack that are not under meaningful human control, independent of their size.
2. A prohibition of swarms of autonomous armed systems, independent of the size of the elements.
3. Qualitative and quantitative limits on swarms of armed systems, e.g. differentiated by numbers of elements, their sizes, ranges and weapons.
4. Lower limits on the sizes of armed UAVs (e.g. 2 m wingspan/length/overall rotor diameter) and on the size of missiles (e.g. 69 mm diameter).
5. Quantitative limits on the holdings of small and very small armed UAVs and of small and very small missiles, e.g. taking the general approach and the particular procedures of the CFE Treaty as role models but striving for global application.

Compliance with such prohibitions and limits can be verified mostly by traditional methods of on-site inspections, manoeuvre observations, demonstrations of new types etc., supported by data exchanges. For measures 1 or 2, secure recording of data needs to be used in addition so that later proof is possible that attacks by uncrewed weapon systems had been under human control.

For the detailed design of these measures, research should investigate various options. Measures 1 and 2 would benefit from more detailed research about verification methods. An important issue for measure 3 is how the combat capabilities of swarms of different structures could be compared roughly, e.g. by a swarm score. For measure 4 it should be studied which lower size limits would be most helpful to prevent or at least contain international destabilisation on the one hand and terrorist uses on the other. Another topic is the possibility of limiting missile uses to defensive ones. Measures 4 and 5 need investigations about the relative role of small and very small armed UAVs and missiles versus bigger systems. On a more general level, the same question should be studied with respect to unarmed UAVs, e.g. for intelligence, surveillance and reconnaissance. Bigger ones are already deployed widely – do small and very small types bring new capabilities with relevant dangers?

The arms-control steps should be supported and complemented by confidence- and security-building measures (CSBMs), incorporating small and very small systems systematically in the CSBMs of the OSCE and expanding similar ones to other regions. In the same vein the transparency measures in the UN framework, that is the Register of Conventional Arms and the Arms Trade Treaty, should incorporate small and very small armed UAVs as well as small and very small missiles, by systematising the definitions of the categories. Here additional research is needed. Research should also be devoted to the question how export controls can include small and very small armed UAVs and missiles better.

Negotiating such new regulations seems remote in the present international situation. Much of co-operative arms control has broken down. The most important countries rather prepare for war and push for military-technological superiority. In these highly problematic developments small and very small armed UAVs and missiles form only small parts. They should be included in limits on wider military technologies that are dangerous to stability and international security.

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