Pervasive Intelligence

The Tempo-Spatiality of Drone Swarms

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Abstract

This article seeks to situate collective or swarm robotics (SR) on a conceptual pane which on the one hand sheds light on the peculiar form of AI which is at play in such systems, whilst on the other hand it considers possible consequences of a widespread use of SR with a focus on swarms of Unmanned Aerial Systems (Swarm UAS). The leading hypothesis of this article is that Swarm Robotics create a multifold "spatial intelligence", ranging from the dynamic morphologies of such collectives via their robust self-organization in changing environments to representations of these environments as distributed 4D-sensor systems. As is shown on the basis of some generative examples from the field of UAS, robot swarms are imagined to literally penetrate space and control it. In contrast to classical forms of surveillance or even "sousveillance", this procedure could be called perveillance.

Upside Down Evolution

Stanislaw Lem allegedly always resisted to be primarily attributed as a science fiction writer. In fact, designations like visionary or utopian seem more appropriate: The edginess of Lem's writing coincides with a comprehensive education in literature, technology, and natural sciences. And it was always driven by a genuine interest in the minute analysis of social phenomena, no matter whether it concerned the future, the present, or the past – although this seems difficult to separate, anyway. As early as 1964, Lem devoted his novel *The Invincible* (see Lem 1973) to a reconceptualization of technological progress. In this story, the crew of the star cruiser *Invincible* is sent on a search mission to an unknown planet. After the arrival, the space explorers make an encounter with a strange form of artificial intelligence: a giant swarm of very simple, but coordinated and cohesively moving micro machines. During their research the crew discovers that these 'pseudo-insects' are the last surviving 'species' of an evolutionary struggle for artificial life between competing war machines. As the destroyed remnants and ruins of sophisticated weaponry tell the expedition team, the relatively under-complex swarming pseudo-insect had proven superior to their monolithic techno-

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logical counterparts. And finally, also the *Invincible* is ascertained of the genuinly undefeatable system on that planet.

Almost twenty years later, Lem picked on this idea again. In his hilarious essay *Weapon Systems of the 21st Century or The Upside Down Evolution* (1983), he describes – as a narrator from the future, and thus in fictional hindsight – the abandonment of the complex but also error-prone and often easily targetable weapons technology of the 20st century in favor of much simpler and smaller cooperating elements:

> The experts of the day called the new military science an 'upside-down evolution', because in nature what came first were the simple, microscopic systems, which then changed over the eons into larger and larger life forms. In the military evolution of the postnuclear period, the exact opposite took place: microminiaturization. (Lem 1983: 35).

Moreover, Lem's technological "involution" (ibid.: 35) towards communicating swarms of "synsects" (for synthetical insects) concurred with a renunciation of traditional artificial intelligence (AI) approaches. When, writes Lem with a wink, for 97,8 % of all human activity – physical as well as mental – intelligence was of minor importance, it was all but reasonable to put so much effort into the (futile) endeavour of simulating human-like intelligence: "What *was* necessary? A command of the situation, skill, care, and enterprise. All these qualities are found in insects." (Ibid.: 29). Thus, from an exact analysis of biological evolution "professors of computer science" would have learnt that the simulation of *artificial instincts* instead of AI was far more feasible and fruitful (ibid.: 30). For Lem, as a consequence, the 21st century became the era of "artificial nonintelligence" (ibid.: 29) featuring "micro-armies". These replaced human soldiers and humanoid automata with swarms of tiny units "which possessed superior combat effectiveness only as a whole (just as a colony of bees was an independent, surviving unit while a single bee was nothing)." (Ibid.: 33)

As with many of his stories, Lem himself shows an extraordinary instinct for future developments, as actual working papers and articles confirm. Authors discuss the advent of a widespread employment of unmanned systems on an interdisciplinary level (see e.g. Bhuta et al.: 2016; Parks and Kaplan 2017; Bender and Thielmann 2018). Germany's *Bundeswehr* faces them as a substitution for lacking manpower and defective high-tech gear (Leidenberger et al.: 2017). At the same time, popular science books like David Hambling's *Swarm Troopers* (2015) collect manifold examples of the limits and shortfalls of sophisticated weaponry for future conflicts in the growing presence of highly mobile and flexible micro machines. Journal articles examine the consequences of a possible mass-production of such systems for postures of military force and political power (see e.g. Goh 2017; Feng and Clover 2017; Page and Tripp 2012). Still others are concerned with an increasing shift of technological leadership from military developments towards commercial innovation cycles and production capacities (Hammes 2016).

The publication of a first video of an allegedly successful text mission of a swarm of 103 *Perdix* drones in October 2016, by the US military widely resonated in news media. (see e.g. Baraniuk 2017; Lamothe 2016). And as of recently, *The Economist* featured an article about the maturing development of autonomous micro robots under the alluding titel “Bot flies” (Economist 2017), and NASA speculates about “Marsbees” for future planetary exploration missions (Bluman et al. 2017). However, although taking examples from the respective background, this article is not about a detailed description of the technical history and possible future of such military gadgetry. Yet it seeks to situate a certain strain of robotics – that is, collective or swarm robotics (SR) – on a conceptual pane which on the one hand sheds light on the peculiar form of AI which is at play in such systems, whilst on the other it considers possible consequences of a widespread use of SR with a focus on swarms of Unmanned Aerial Systems (Swarm UAS).

Connecting to Lem’s term of “artificial nonintelligence”, part II of this article construes crucial *tempo-spatial features* of swarm intelligence (SI) and swarm robotics (SR), thereby including some vanishing lines back to pioneering work in the field of embodied AI. The subsequent part (III) then turns towards concrete *tempo-spatial directions* which SR technology has taken recently. With some recent examples of Swarm UAS – that is, (semi-) autonomous drone swarms – it depicts research projects which endeavor to realize operational Swarm UAS by constructing them along the lines of simulations of animal behaviors. And finally, in its last part (IV), the article assesses a number of recent military analyses which ponder upon the possible strategic consequences of an expected future widespread use of SR which bears surprising ressemblances to Lem’s lucid essay.

One leading hypothesis of this article is that Swarm Robotics create a threefold ‘spatial intelligence’: First, it consists of the dynamically changing morphologies of such collectives, second, of their robust self-organization in changing environments, and third, it creates representations of these environments as distributed 4D-sensor systems. Its functioning is thereby grounded in the particular “artificial nonintelligence” of swarms which replace traditional AI features with ‘streetsmart’ connections of movements, locations, and spatial features. This results in a particular *intelligence of movement* or *spatial intelligence* which is only effected by the interaction and communication processes of the swarm members. To the more, the massive parallelism of these collectives enables the distribution of different functions, e.g. for sensing purposes or for transmitting signals, on different swarm members. Thus, as this article will show on the basis of some generative examples from the field of UAS, robot swarms are imagined to literally penetrate space and control it. In contrast to classical forms of surveillance or even “sousveillance” (Mann et al. 2004), this procedure could be called *perveillance*.

An ensuing second hypothesis is that Swarm UAS which operate (semi-) autonomously in dynamic environments can be perceived as exemplary materializations of phenomena which have been discussed under the catchphrase *media ecology* in recent years. The term reflects both an ubiquitous dissemination of media (Featherstone 2009) and the pervasion of everyday life and objects by ubiquituous computing (Weiser 1991), algorithmic and sensor environments (Thrift 2007; Gabrys 2007), RFID technologies (Hayles 2009) and the so-called Internet of Things (see e.g. Sprenger/Engemann 2015; Easterling 2014) which instigated an intensified occupation of media theory with ecological concepts, metaphors, and their historical unfolding (e.g. Hörl 2017; Munster 2013; Löffler/Sprenger 2016). Adding to this discourse, a critical consideration of research projects which explore the capabilities of micro drones to autonomously 'live' in dynamic environments over long periods could shed further light on contemporary entanglements of natural and technological environments. Such UAS would, for instance, take advantage from atmospheric layers for gliding like seabirds (see e.g. Langelaan and Roy 2009) as well as from existing electric lines for recharging (see e.g. Gupta et al. 2010). And with a set of behaviors or 'instincts' simulating predatory birds or bats – like lurking in hideouts or perching from lookouts – they could be enabled to autonomously 'pervey' a given area for long periods (see Hambling 2014; US Air Force 2014).

Fast, Cheap, and Out of Control

In view of the infamous paper *Fast, cheap, and out of control. A Robot Invasion of the Solar System* (Brooks and Flynn, 1989), it seems rather unlikely that roboticist Rodney A. Brooks was not a dedicated reader of Lem's works. Brooks was searching for an alternative way to achieve intelligent behavior in machines which contested the cognitivist approaches of GOFAI: He believed that only in relation and interaction with the complexities of a surrounding environment, robots would be capable of developing intelligent behavior. The key term was *embeddedness*, and the conceptual principle was *bottom-up*: Knowledge about the world should rather be computed on-the-run by small robots capable of sensing only those conditions of their environment and react accordingly that were needed to fulfill certain tasks. It was a plain rejection of those attempts which sought to construct complicated robots with complex artificial brains containing large pre-programmed 'concepts' about the surrounding world (see Brooks 1990). Soon, his Lab and offices at the MIT began to resemble a techno-zoo crowded by small robot prototypes – delightfully featured also in a TV documentary (Erol Morris, US 1997). The most popular of these robots was *Genghis*, a six-legged insectoid robot based on a 'subsumption architecture' without a central controller. Genghis already followed swarm principles internally – its legs were driven by independent motors, and 'walking' was not programmed into the robot, but emerged from the legs constantly exchanging information about their respective positions. This lead to the stunning effect that it was not the *robot* which was walking with his legs, but it was the *legs* that walked the robot. However clumsy these first emergent steps might have been – Brooks together with Anita M. Flynn pictured the future of such machines in bold strokes (1989: 478):

> Complex systems and complex missions take years of planning and force launches to become incredibly expensive. The longer the planning and the more expensive the mission, the more catastrophic if it fails. The solution has always been to plan better, add redundancy, test thoroughly and use high quality components. Based on our experience [...] we argue here for cheap, fast missions using large numbers of mass produced simple autonomous robots that are small by today's standards (1 to 2 kg). We argue that the time between mission conception and implementation can be radically reduced, that launch mass can be slashed, that totally autonomous robots can be more reliable than ground controlled robots, and that large numbers of robots can change the tradeoff between reliability of individual components and overall mission success. Lastly, we suggest that within a few years it will be possible at modest cost to invade a planet with millions of tiny robots.

This part already compiles almost all ingredients that also today make swarm robotics a promising approach when it comes to coping with complex demands in unpredictable environmental conditions – its, at least conceptually, greater robustness, flexibility, reliability, and scalability (see also Brooks 1990). Or, simply put: "[U]sing swarms is the same as 'getting a bunch of small cheap dumb things to do the same job as an expensive smart thing'." (Corner and Lamont 2004: 335)

Brooks thus indirectly presented crucial elements of a swarm intelligence mindset which had been formulated in the same year of 1989 on a NATO robotics conference by engineers Gerardo Beni and Jing Wang (1989). Albeit referring to computerized modelling and simulation techniques based on cellular automata, they invented the term 'swarm intelligence' in the context of robotics and inspired a wave of busy development of SI systems in various scientific areas (see Vehlken 2012). SI is grounded in the idea that the complex adaptive behavior of a system at the global level can be effected by multiple parallel interactions of very simply constructed individuals at the local level which follow a set of only a few behavioural rules. Compelling cases such as CGI designer Craig Reynolds' *Boids* simulation from 1986 rely on just three steering rules: avoidance (avoid collision with local flock mates), alignment (steer towards the average heading of local flock mates), and cohesion (steer towards the locally perceived center of the flock) (Fig. 1 and 2). These produced swarming behaviours of computational agents similar to what one finds in bird flocks or fish schools (Reynolds 1987; see e.g. Couzin and Krause 2003). Other approaches simulate communication through a process called *stigmergy*, using digital traces instead of chemical signs which agents leave in the model environments like some types of social insects do in their natural habitat (Bonabeau et al. 1999; Gaudiano et al. 2003) (Fig. 3).

Such collectives possess certain abilities that are lacking in their component parts. Whereas an individual member of a swarm commands only a limited understanding of its environment, the collective as a whole is able to adapt nearly flawlessly to the changing conditions of its surroundings. Quite to the contrary, it is precisely a certain amount of randomness or random noise introduced from the environment which enhances the mobile performance of such biological

Fig. 1: Behavioural rules of the flocking algorithm of Craig Reynolds' Boids-Simulation

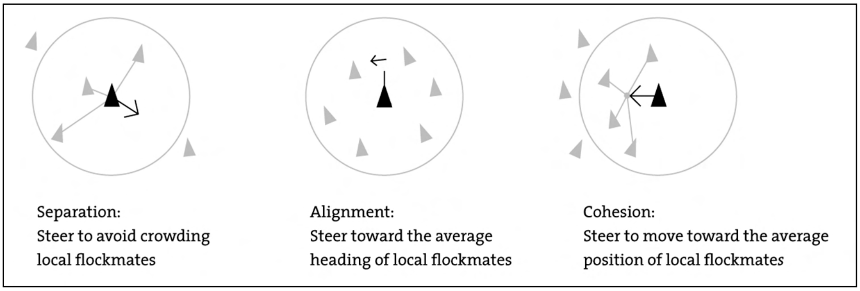


Fig. 2: Emergent effect of obstacle avoidance in Reynolds' Boids-Simulation

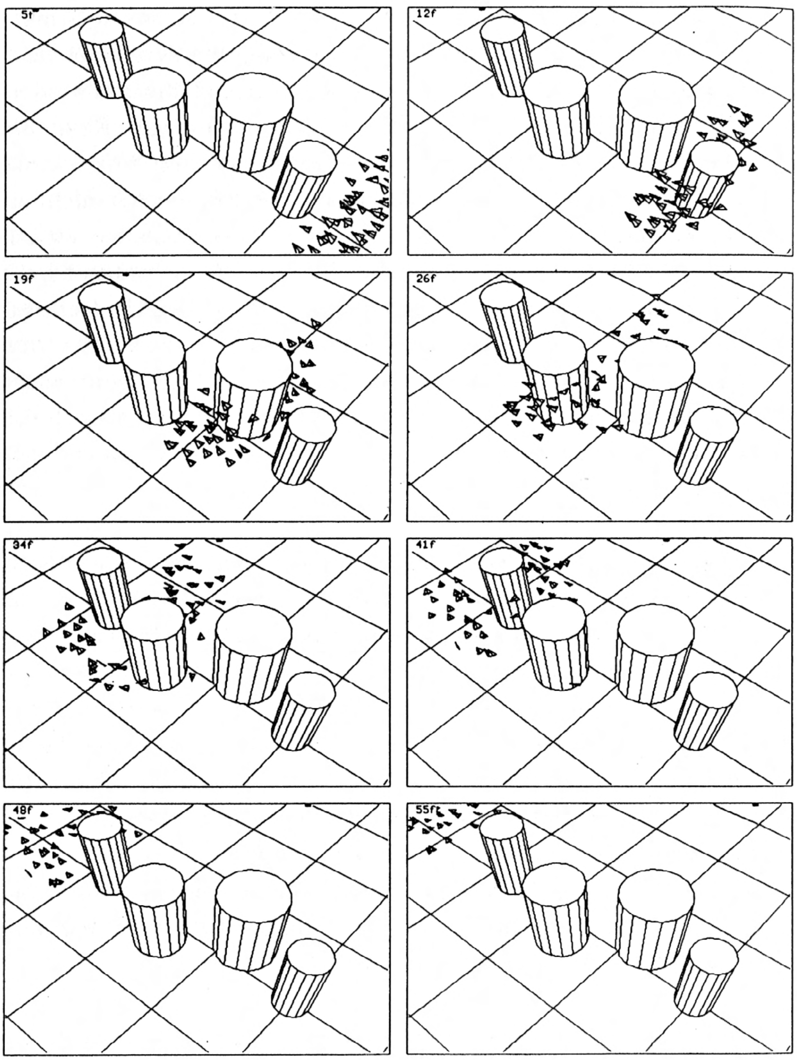
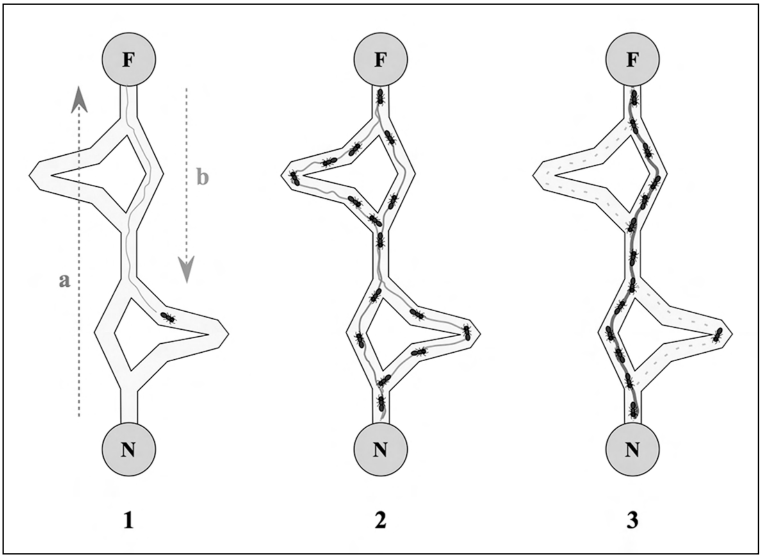


Fig. 3: Route optimization by positive feedback: Ants following pheromone trails



collectives. Without recourse to an overriding authority or hierarchy, the adaptive movements of swarms emerge from rapid information exchange among swarm members in local neighborhoods. Thus within swarms, the quantity of local data transmission is converted into new collective qualities, that is, collective behaviors which are not existing in the individual capacities of the swarm members. In 1999, one early seminal publication for the field thus introduced the approach as follows:

> Researchers have good reasons to find swarm intelligence appealing: at a time when the world is becoming so complex that no single human being can understand it, when information (and not the lack of it) is threatening our lives, when software systems become so intractable that they can no longer be controlled, swarm intelligence offers an alternative way of designing 'intelligent' systems, in which autonomy, emergence, and distributed functioning replace control, preprogramming, and centralization. (Bonabeau et al. 1999: xi)

The epistemological foundations of that particular mindset, however, are more intricate than such usual bionic narratives of bio-inspired technical systems. Swarms, flocks and schools first emerged as operational collective structures by means of the reciprocal computerization of biology and biologization of computer science. In a recursive loop, swarming in social insects, flocking birds or schooling fish inspired agent-based modelling and simulation (ABM), which in turn provided biology researchers with enduring knowledge about their dynamic objects of research. This conglomerate led to the development of advanced, software-based 'particle systems'.

SI has thus become a fundamental cultural technique for governing tempo-spatial processes (see Vehlken 2013) which fundamentally differs from the contemporary mainstream of AI. Whereas a good part of the rejunvenation of AI is based on so-called 'deep learning' techniques for Artificial Neural Networks (ANN) which profit from formely inaccessible or simply inexisting quantities of digital data and abundant computing power, SI could be entitled an intelligence for motion and coordination, developing in real-time. As an effect of their 'conspatiality' in local neighborhoods, SI and SR systems are described as "well-suited for tasks that are concerned with the state of a space." (Beni 2008a: 17) Developing from these grounds, this article thus designates SI as a *spatial intelligence*: Its field of application has extended from the self-organized coordination of industrial production processes to logistics planning and to the optimization of network protocols (Engelbrecht, 2005). Moreover, the 'artificial nonintelligence' of swarms can play a role wherever there are time-sensitive problems of coordination and transference between numerous particles; such problems present themselves, for instance, in traffic simulations, social simulations, panic simulations, consumer simulations, epidemic simulations, simulations of animal collectives, and even in the behavior of aerosol in climate models.

As a matter of fact, especially in routing and logistics, a number of SI applications have proven superior to competing approaches: For instance, in AntNet, a routing protocol developed by SI pioneer Mario Dorigo et al., packets of information hop from node to node and thereby leave a digital signature that signals the 'quality' of their trip as they do so. Other packets evaluate the trails thus created and choose accordingly: "In computer simulations and tests on small-scale networks, AntNet has been shown to outperform existing routing protocols. It is better able to adapt to changed conditions (for example, increased traffic) and has a more robust resistance to node failures." (Economist 2010) Despite substantial corporate interest in such routing algorithms, the huge costs of hardware replacement which they would require kept their widespread implementation away from happening. However, as the above article does not fail to mention, the technology "looks promising [...] for *ad hoc* mobile networks" like those used by the armed forces and civil-protection agencies. And thus, their applicability points exactly in the direction of interconnected autonomous mobile robots and Swarm UAS – systems where more centralized approaches "frequently lead to exponential increases in communication bandwith requirements and in the size of the controlling software", as well as they are dependent on the "availability of global information". (Gaudiano et al. 2003: 1)

Swarms create information by means of formation. They generate a specific secondary environment – the moving collective – which surrounds the swarm-individuals and facilitates adaptive processes by way of rapid nonlinear information transmission between these individuals in local neighbourhoods. As media theorist Eugene Thacker put it: "The parts are not subservient to the whole – both exist simultaneously and because of each other. [...] [A] swarm does not exist at a local or global level, but at a third level, where multiplicity and relation intersect."

(Thacker 2004) This third level precisely designates a specific adaptive environment which mediates between external environmental forces and the behavior of swarm individuals.

Turning back to the introducing example of this section, it becomes clear that Rodney Brooks' envisioned space invaders (and their actual NASA 'Marsbees' revenants) would take advantage of the allegedly superior capabilities of swarming collectives to explore unknown environments or areas which are difficult to access: In comparison to larger and more sophisticated single robots, drones or – in Brooks' context of space missions – rovers, individual swarm members were able to swiftly scan different areas, communicate decisive information back to near neighbors, and thus contribute to a collaborative and parallel process of collecting intelligence. SR, says Gerardo Beni, would benefit from the fact that "[t]he production of order by disordered action appears as a basic characteristic of swarms." (Beni 2008b: 153) This is due to the functioning of swarms where "the units operate with no central control and no global clock." (Beni 2008b: 154) Swarm systems update *partially synchronous*:

> In fact, during an UC [updating circle, SV], any unit may update more than once; also it may update simultaneously with any number of other units; and, in general, the order of updating, the number of repeated updates, and the number/identity of units updating simultaneously are all events that occur at random durcing any UC. We call the swarm type of updating *Partial Random Synchronicity (PRS)*. (Ibid.: 157)

This allows for a greater flexibility of the individual swarm members to adapt to external factors, and they each can only stimulate a limited number of next neighbors to similar increased or decreased activity due to their restricted interaction range. The specified size of a neighborhood and the resulting spatial structure and morphology of mobile collectives therefore formats the development of synchronization processes in the collective. Time-lags thus do not automatically lead to less sustainable systems, but on the contrary, it is precisely the synchronization (not simultaneity) via local information transmission which effects a strenghtening or weakening of movement reactions to external influences. Henceforth, asynchronicity or "order by disordered action" in swarms becomes operative by means of spatial dispositions. And consequently, the dynamic equilibrium of robot collectives is not only dependent from a contemporary reaction to external stimuli, but also from its 'conspatial' arrangement which is based on the parametrization of position-, distance-, and speed-measuring sensors. Such features even more apply for today's UAS swarms as these come with airborne abilities that Brooks' insectoid robots just would have dreamed of (instead of electric sheep). It is not a coincidence that the larger part of SR research today is occupied with UAS – and as an effect, also this article in the following focuses on aerial robots –, as these are able to navigate more easily in three dimensions without having to cope with the restrictions of grounded vehicles in two-dimensional environments.

The potential maneouverability of Swarm UAS adds an additional aspect to SI's concern of the state of a space: Not only constitutes the spatial intelligence of swarms their self-organisation capacities – coordinating the movements of cohesive collectives while adapting to external forces –, but it also provides the means to thereby 'read' or 'record' various data about the state of a surrounding space or environment. 'Intelligence', on this pane, first and foremost portends *reconaissance*. For instance, if a swarm member would identify something of interest with regard to a pre-defined mission goal, it could attract additional members searching in less promising places to the respective area. As computer scientist Erol Sahin put it: "[D]istributed sensing by large numbers of individuals can increase the total signal-to-noise ratio of the system." (Sahin 2008: 11). Together, swarm members could deliver a detailed view of a feature or object in that area – e. g., form different angles at the same time – more quickly. In a way, Swarm UAS thus are physical materializations of a mathematical search procedure from the field of SI known as *Particle Swarm Optimization* (PSO). PSO algorithms are inspired by search strategies of flocking birds looking for feeding sites which are scattered in a given area. By implementing the 'cornfield vector' of ornithologist Frank Heppner, PSO developers James Kennedy und Russell Eberhart modeled a search algorithm for maxima and minima of non-linear functions and for multi-objective optimization problems, using randomly dispersed particles which step-by-step would explore the search space, compare their relative positions, and eventually converge around local – or, even better – global optima (Russell and Eberhart 1995: 1942–1948; Heppner 1990: 233–238; Engelbrecht 2005; Poli et al. 2007: 33–57).

It is precisely this three-fold *spatial intelligence* and comparatively simple approach to tackle complex problems by distributed self-organization capacities which characterized SI as a fruitful AI subfield. However, against the backdrop of recent developments in robotics – and particularily UAS – hardware, not only its possible areas of applications have expanded, but also its bionic or bio-mimetic tell-tale of designing artificial robot swarms along the lines of 'mother nature' is proliferated. The following section further pursues the abovementioned spatial intelligence-dimension of *reconaissance*. It argues that contemporary research projects towards Swarm UAS take on interweaving technological and ecological environments in novel ways and thus point towards a reconceptualization of 'controlling' space.

Perveillance by Artificially Intelligent Behavior

Whilst SI and Agent-based Modelling and Simulation (ABM) software applications began to flourish from the mid-1990s onwards, Swarm Robotic invasions had been a long time coming. It took more than fifteen years until Erol Sahin published the seminal volume *Swarm Robotics* (Sahin 2008) and defined SR as "the study of how a large number of relatively simple physically embodied agents can be designed such that a desired collective behavior emerges from the local interactions among agents and between the agents and the environment." (Sahin 2008: 12) For this volume, Gerardo Beni authored an introduction with the title *From Swarm Intelligence to Swarm Robotics* (Beni 2008a) in which he directly addressed the issue of lagging behind:

> [T]he original application of the term [SI] (to robotic systems) did not grow as fast. One of the reasons is that the swarm intelligent robot is really a very advanced machine and the realization of such a system is a distant goal (but still a good research and engineering problem). Meanwhile, it is already very difficult to make small groups of robots do something useful. (Ibid. 2008a: 7)

Even if the volume included reports on pioneering projects like *SWARM-BOTS* (Groß et al. 2006) and *I-SWARM* (Seyfried et al. 2005), the featured discourse remained mostly 'idiosyncratic': It circled around questions of how to engineer functioning robot collectives in the first place, thereby merely rendering diverse computer simulation softwares more realistic by introducing a certain 'hardware realism', that is, e.g. taking into account specific bandwith restrictions or compromised positioning routines of existing physical robots. At the same time, the mentioning of possible application areas was universally rubricated under 'future developments'. Researchers imagined a whole range of possible applications like collective minesweeping or the distributed monitoring of geographic spaces and eco-systems. Swarming elements were imagined to also take on counter measures by self-assembling into blockings against leakages of hazardous materials, thereby being scalable according to the graveness of a situation. The swarm-bots would synchronize with environmental events in space by tracking, anticipating, and levelling them by self-formation (see e.g. Beni 2008b).

This time-lag is – apart from the challenges of engineering working physical systems instead of virtual agents – also due to a changing understanding of SI. In 2000, Sanza Kazadi introduced the term *Swarm Engineering* recognizing that "the design of predictable, controllable swarms with well-defined global goals and provable minimal conditions" was mandatory in the field of robotics. "To the swarm engineer", he notes, "the important points in the design of a swarm are that the swarm will do precisely what it is designed to do, and that it will do so reliably and on time." (Brambilla et al. 2012, 2, cf. Kazadi 2000). The robots's being out-of-control – as in Brooks' provocative article header – thus had to be framed by rigidly determined objectives and behavioral control in order to prevent undesired outcomes: Bluntly put, it is much more expensive and time-consuming to deal with UAS crashing into the ground in real-world experiments than it is with boids crashing into computer-simulated obstacles.

Kazadi's perspective, whilst also seeking to overcome seemingly unproductive emerging patterns in animal collectives – like e.g. the circular milling which is observable in ants – on the other hand somehow compromised the conceptual juxtaposition of SR to animal swarms, thus broadening the respective research field to more general collective robotic systems with sometimes little ressemblance to the abovementioned features of biological and computational swarms. Physical proximity – which is mandatory for bird flocks or fish schools – or stigmergy, that is, communication per deposition of cues in the environments – like the pheromone trails in social insects – in Swarm UAS are often replaced by neighborhoods which are defined by the capability of intra-platform datalinks or backlinks to ground control stations. Conceptually, they are thus capable of maintaining cohesion even if they are rather widely distributed over an area as long as they stay in the range of their communication systems. This feature makes them all the more attractive as distributed sensor systems which bring into congruence swarm space and environmental space. Furthermore, swarm-engineered UAS like the abovementioned *Perdix* drone collective are based on a principle which sounds rather perplexing to the humanist ear: "directed autonomy" (Page and Tripp 2012: 6): Human mission operators, when following the drone's movements on a tactical screen, will put in certain general orders, so-called 'plays' – like, e. g. 'encircle area X' or 'follow object Y'. The *Perdix* system is designed to then interpret these orders and execute them autonomously according to local circumstances (see Feng and Clover 2017). Or, in another approach, the conspatiality of swarms enables an UAS operator to direct a whole collective by taking control over only one swarm member – the others would then automatically follow its lead. (see Scharre 2014)

Certainly, there are quite a few technical as well as ethical repercussions of such approaches to keep humans 'in the loop' which have to be considered. (see e. g. Butha et al.: 2017) And if today a search on *IEEE Xplore* generates about 1,500 hits for 'swarm robotics', it seems mandatory to separate the wheat from the chaff, not only in terms of the permitted level of autonomy involved, but also in terms of the functioning and operativity under realistic conditions of the respective collective robotic systems. Nonetheless, one has to acknowledge a rather profound transformation within the last 10 years that brought SR out of a mere technological niche and to – as mentioned in the introduction – a prominent position in the current discourse of autonomous robotics. Combined with at least two additional effects, that is, first, the easier accessibility of reliable and lightweight UAS building parts, sensory and communication equipment, and software, and second, a significant investment in micro-UAS, not seldom with military funding – take as an example the US-American MAST (Micro Autonomous System and Technology) and DCIST (Distributed and Collaborative Intelligent Systems and Technology) programs (see Economist 2017) – this expansion quite likely enforces the assessment also of the possible socio-political-technical implications involved. An assessment that prolongates existing *Politics of Swarms* (Parikka 2008) to their physical embedding in machinic collectives, and that seems to reflect a novel urgency to discuss their *spatial intelligence* as a particular media-ecological feature.

The objective of Swarm UAS to gather information about surrounding environments portends the *reconnaissance* dimension of 'intelligence'. Understood as distributed sensor systems they are *first* designed to collect data "across spatial, temporal and spectral domains" (Page and Tripp 2012: 4), with certain Swarm UAS developed along the purpose of *pervading* space in three dimensions and time. This way, such systems principally could offer more detailed spatial information than single platforms, from large drones to satellites. (see e.g. Colomina and Molina 2013: 79) *Second*, with novel technological features that could overcome today's main shortfall of UAS – that is, short operation time due to limited battery power – a substantial part of Swarm UAS development is occupied with constructing robots that could become *permanent* parts of a hybrid techno-ecological environment: On the one hand by ways of bio-mimicking animal behavior not unlike the ones depicted in Stanislaw Lem's novel, and on the other by also integrating technical infrastructures into this set of behavior. And *third*, Swarm UAS could themselves be used as effectors of particular environments on the electromagnetic level, e.g. as instant, wireless communication networks (see Kruzelecki 2015; Pacheco et al. 2012) or, in the military field of Electromagnetic Warfare (EW), as jammers or distributed beamforming radar platforms (see e.g. Kocaman 2008).

Turning back to Rodney Brook's article for a last time, it highlighted a further aspect which is also of eminent relevance today – economies of scale: Small robots can be mass-produced, can be largely constructed from off-the-shelf components (see e.g. Scharre 2014), or can even be 3D-printed on site (see e.g. Marks 2011; Balazs and Rotner 2013) because their capabilities profoundly are created in their software and communication routines and not by the sophistication of their hardware. Indeed, technologies developed for smartphones – like miniature cameras, GPS navigation, radio communication, data processing power, sensors for measuring its relative position, acceleration, and environmental information (sound, pressure, humidity etc.) – are appropriate to the requirements of miniature UAS (see e.g. Cevik 2012: 602). So is a shared need for minimal weight, size, and power. (see Hambling 2015: 4) The immense investments of the smartphone industry into advancing such technologies thus effectuated rapidly improving capabilities and a simplyfied usage of UAS, and as a consequence, a fast-growing market for commercial drones. But nonetheless, it is an oversimplyfication to speak of such micro drones as smartphones on wings, with "the wings [as] the cheap part". (Hambling 2015: 4) Intensive research in various propelling technologies – from winged layouts to multicopter technology (e.g. Vázárheyli et al. 2014) to bio-inspired, insect-like flapping techniques (De Croon et al. 2016) or to the insect-like aerodynamics generated by cyclocopter technology which lack any biological analogy (see Economist 2017) – suggests that different objective areas would also demand quite different types of drones.

As of today, UAS are employed in a wide variety of application fields – from public safety and policing via infrastructure surveillance and environmental or wildlife surveys to Lady Gaga's *NFL Super Bowl* 2017 stage show (see more examples on Unmanned Aerial Online 2018). And this availability of off-the shelf solutions combined with low entry costs and rapid evolution makes it attractive to harness the advantages of swarming by customizing commercial drones with SI algorithms. Swarm UAS offer substantial advantage over single UASs in research fields where the parallel coverage of wide areas is paramount, e.g. in the generation of spatial data and maps for general use (Colomina and Molina 2014: 79), in environmental or wildlife monitoring, in agriculture, in urban studies, or in military reconaissance. Following principles like PSO, areas of interest could be identified easier and faster, and by collecting data in parallel, scanning and surveillance tasks could also be accelerated.

> Furthermore, fault-tolerance is inherently provided by the use of swarms, because a single drone can be removed with a limited impact on the overall formation. Swarms can also provide scalability, i.e., adding or removing drones from a swarm, in order to better adapt to changing conditions or to simply replace one or more UAVs experiencing issues or battery depletion. (Bacco et al. 2017: 2)

In addition, by producing low-altitude remote sensing (LARS) – be it optical, infrared, acoustic, or other – in high definition, small drones not only reduce operation costs, but provide data which are unattainable by larger UAVs or reconnaissance satellites: the data recovery of small drones remains independ from atmospheric interferences, clouds or other objects which block top-down sensing, and they fly at much lower speeds and thus create higher point densities. (see Carbomap 2014) Some systems are capable of automatically stitching together high-resolution images in a mosaic map, with data processing carried out on board. Only when something of interest is identified, this data is send back to the ground control unit for further analysis. This way, the necessary bandwith requirements can be kept low. (Hambling 2015: 109) A concrete example is *Carbomap's* successful attempt to measure the canopy height of rainforests by airborne LIDAR (Light Detection and Ranging). This technology, recently having become famous by the airborne scanning of a (sufficiently well-known) Maya city under a closed rainforest canopy, enables 3D maps to be created, and further relevant metrics such as forest carbon to be calculated or estimated – a technology which could also be used for the exploration of the internal spaces of built structures.

However, the abovementioned pervasive actions of Swarm UAS still severely suffer from one crucial disadvantage – the limited operation time. This typically ranges from one hour to a few minutes in the case of micro-UAS. Hence, on the one hand, researchers seek to improve power supply by turning to novel battery technology, fuel cells, or solar power – the latter is especially suitable in micro drones because of their better surface-to-weight ratio compared to larger UAVs or planes (Hambling 2015: 133–136). On the other, some developers take certain animal behaviors as a starting point and try to simulate them with their UAS. In attempts like the following, Rodney Brooks' early research clearly resonates, and the respective UAS can be depicted as technologies which mediate between and capitalize from both natural and technological environments.

For instance, researchers simulate the flight patterns of seabirds – the respective data extracted by precise GPS trackers placed on living albatrosses – to extend operation time, using drones that learn to orient themselves in relation to airflows and to plan their trajectories through different layers of air by continuously calculating a wind field estimation model fed by data from computer simulations and several sensors (Hambling 2014; Langelaan and Roy 2009). *Vishwa Robotics* constructs UAS which use the ability to perch – that is, to simultaneously save power between flight times and gather intelligence from more stable viewpoints than while hovering in mid-air. With the high-speed analysis of landing birds, the researchers identified different landing strategies and developed simplified artificial legs which would allow for landing maneouvers similar to birds, both on flat surfaces and on branches (Gajjar 2012). Yet the ability to perch autonomously also includes the necessity to identify and steer to suitable locations. Perching sensors could use visual sensors to indentify, select and survey and exploit such places by creating 3D models of possible landing areas. Other approaches let the drones spiralling down and use cameras to detect possible perches by the shadows they cast, because these give useful 3D information (see e. g. Bosch et al. 2006).

Yet different research projects develop such concepts even further. If drones would perch or roost on particular places – like power lines – they could be enabled to not only save power, but to actually recharge. Design Research Associate's *Bat Hook* can be tossed over a power line where its sharp edge will cut through the insulation. The device also works as an AC/DC converter which regulates high-voltage power down for charging electronics (Hambling 2015: 129). *Urban Beat Cop*, a prototype mobile CCTV system, is equipped with a similar tool to possibly become a permanent part of urban landscapes. His design aims at generating the ability to carry out missions that continue indefinetely (Launchstories 2018). And incidentially, this could further advance societal control measures as "drones [become] not just tactical devices for patrolling or dealing with a particular incident […]. The Urban Beat Cop design includes software to carry out some types of pattern-of-life monitoring automatically. It could keep track of the comings and goings of specific vehicles in an area and potentially even individuals. It may not be Big Brother watching you in the future, but a small perching drone". (Hambling 2015: 130)

Hence, these latter approaches aim at adding a function of permanence to the spatial and behavioral intelligence of UAS which further integrates them with features of their ecological and technological environment – from airflows to electric currents. Besides the abovementioned spatial-intelligent aspects of dynamic self-organization as collective structures and of providing advanced reconaissance capabilities when utilized as distributed sensor networks, this function of permanence thus fosters a novel perspective: It understands such UAS as bio- or zoo-technological hybrids which mediate between and actively intertwine biological and machine ecologies. And this aspect is yet bolstered by Swarm UAS system which, one might say, act as particular media ecologies of their own right. For instance, the *Swarming Micro Air Vehicle Network* (SMAVNET) project of EPFL Lausanne explores the benefits of so-called Flying Ad-Hoc Networks (FANET) for cases of catastrophic events when ordinary communication networks are not available or out of service. Flying ad-hoc networks detect and localize any WiFi devices by detecting their WiFi packets. Since commercial WiFi devices such as smartphones, tablets, or laptops periodically transmit a signaling packet, the drone swarm can learn and processes various parameters by accessing those packets, including the power received by the antenna. By comparing their power, the position of the transmitter can be estimated while it remains completely unaware of the search operation. Thus, the system can connect and coordinate rescue teams and localize victims (Kruzelecki 2015). But obviously, such technology could also be used for other – e. g., military – reconaissance tasks.

By all means, one has to keep in mind that most of these examples still are on rather early stages of their development, and that, as said before, the employment of working Swarm UAS of whatever size is still in its infancy. However, one can clearly notice that, on the one hand, rather rapid advances in robotics have had a profound effect also on the 'materialization' of existing computational SI concepts and algorithms into robot collectives. And that, on the other, this stirred up a lively discourse as to possible socio-political consequences of a hypothetically widespread future use of such "artifical nonintelligence" – a discourse which more often than not recharges earlier concepts of the eeriness of swarms (see e. g. Vehlken 2013b) with contemporary culturally pessimistic accounts of autonomous robotics.

Weapons of Mass Production, or: Misuse of Consumer Electronics

In certain ways, one of the most bizarre weapons development projects of WWII already incorporated some of the features which make Swarm UAS nowadays a valuable research area. Initiated by the dentist, dandy and inventor Lyte S. Adams (see Pias 2007: 306), the US Military from 1942–45 carried out *Project X-Ray*. It was aimed at constructing a "vector method of incinerary bombing" (Couffer 1992: 11) by using bombs filled with bats equipped with tiny explosives which would be released in mid-air over Japanese cities, spread out to naturally seek refuge under roofs of houses, and then incinerate the hideouts with a newly produced chemical agent later to be known as napalm. However, unlike its mission goal suggested, the weapon was highly undirected, uncontrollable – this was proven by a failed test when six armed bats escaped the laboratory at Carlsbad Auxiliary Airfield and lit up several buildings – and, even worse for military strategists, their effects were incalculable. Finally, things went bad for the bat bomb when another device for attacking Japanese cities and for creating "very widespread destruction" (Fieser 1964) was mission-ready earlier and promised greater efficiency in terms of manufacturing and destruction. Nevertheless, as Claus Pias pointed out, the bat bomb as an incalculable, areawide, suprising and compact weapon structurally corresponded to the device, that is, the atomic bomb. (see Pias 2007: 315) Apart from the effect that the bat bomb – at least in theory – would have been horrifying because of the invisibility of the effectors: A dispersed bat attack would not be identifiable as an attack but would appear as a mere environmental disaster. And this would have been quite the opposite of giant blasts and iconic mushroom clouds.

Swarm UAS today have the potential to realize more refined 'vector methods' than these eerie historical forerunners. In the viewpoint of a number of military analysts, recent developments in UAS technology as those described above thus are likely to have an immenent effect on the posture of military force. If these 'bunches of small cheap dumb things' also in warfare could do the same job as an expensive smart weapon, a change of direction in military strategy and thinking would be at hand. These considerations turn upside down the quote of Friedrich Kittler that "entertainment industry, in the truest sense of the word, is a misuse of military equipment" (Kittler 1986: 149, trans. SV): Nowadays, it rather seems to be the military that misuses consumer electronics.

"Quantity has a quality all its own" – what has been a contemptuous quote by Joseph Stalin in WWII times and has long been displaced by the trend of the past quarter of a century to deploy fewer but more advanced (and expensive) weapons platforms of high complexity could be reversed by swarm technology (Feng and Clover 2017): "The next generation of weapons may see sophisticated technology systems outdone by the sheer numbers of autonomous swarms." Hence, being the manufacturing center of the commercial drone and smartphone industry could generate competitive advantages. It is hardly a coincidence that in China, private sector manufacturers already have been co-opted to work for the People's Liberation Army. (Feng and Clover 2017) This way, military institutions also try to incorporate the nowadays much faster innovation and development cycles of private manufacturers. And if at one future stage of development, the mass-production of Swarm UAS became feasible, this could also provide smaller countries and even groups "with capabilities that used to be the preserve of major powers" and complicate possible responses to various crisis our the ability to influence events with military force. (see Hammes 2016: 8) This completely turns around the structural equivalence of WWII bat bombs and nuclear weapons which was noted by Pias:

> Swarm technology, say defence experts, is attractive [...] as it would allow [...] to project force with a lower probability of military confrontation. Drones, unlike fighter jets or aircraft carriers, are less threatening and can be shot down or captured without triggering a military escalation. In December, China seized a US underwater drone in the South China Sea, which the PLA then handed back after a few days. This would have triggered a major crisis had it been a manned vehicle. (Feng and Clover 2017)

Yet such a conclusion remains just as speculative as some scenarios which point into other directions, stating that Swarm UAS could contradict the established fact that air power cannot hold ground. However, on the basis of improved identification and targeting capacities – whose drive also primarily stems from the commercial sector and further blurs the distinguishability of military and civil applications (Feng and Clover 2017) – and in congruence with some of the technological approaches mentioned in the third section of this text, swarm drones could be enabled to occupy an area and 'pervey' it for a long period of time, and also to carry out more precise strikes in far greater numbers than common drone types. (Hambling 2015: 288) In consequence, some authors already imagine the dawn of a new age in military strategy: "[T]he nuclear balance is maintained because neither side can disable the other's startegic weapons with a first strike. Swarms might change this balance and make first strikes possible – or strikes by non-nuclear powers seeking to disarm nuclear ones." (Hambling 2015: 302)

Around the year 2000, 'swarming' began to be discussed in the context of an emerging doctrine of network centric warfare in the US military. Nonetheless, when authors like Sean Edwards (2001) or James Arquila and David Ronfeldt (2000) depicted biological, historical and future scenarios of swarming, the term was employed in a mere metaphorical sense. It subsumed all sorts of cooperative, networked actions on the battlefield, it was focusing primarily on tactics, more precisely to a turn to special forces operations coordinated by superior network centric warfare capabilities, and it thus still put human soldiers in its center. (Kaufmann 2007) Swarm UAS, however, in the words of a military strategist, mark a shift to "true swarming":

> Emerging robotic technologies will allow tomorrow's forces to fight as a swarm, with greater mass, coordination, intelligence and speed than today's networked forces. Low-cost uninhabited systems can be built in large numbers, [...] overwhelming enemy defenses by their sheer numbers. Networked, cooperative autonomous systems will be capable of true swarming – cooperative behavior among distributed elements that gives rise to a coherent, intelligent whole. And automation will enable greater speed in warfare, with humans struggling to keep pace with the faster reaction times of machines. The result will be a paradigm shift in warfare where mass once again becomes a decisive factor on the battlefield, where having the most intelligent algorithms may be more important than having the best hardware, and where the quickening pace of battle threatens to take control increasingly out of the hands of humans. (Scharre 2014: 10)

This type of AI – as has been mentioned above – consists of the combined abilities of autonomously coordinated movement and navigation, distributed sensing and multi-spectral imaging. Its capability of collective self-organization which oscillates between dispersion and concentration can make them efficient as attack weapons and likewise, in comparison to single platform systems, it reduces the danger of being detected or shot down. Or, as Scharre puts it: "Mass allows the *graceful degradation* of combat power as individual platforms are attrited, as opposed to a sharp loss in combat power if a single, more exquisite platform is lost. Offensive salvos can *saturate enemy defenses*. Most defenses can only handle so many threats at one time." (Scharre 2014: 14). Major movie productions from *The Matrix Revolutions* (Lana and Lilly Wachowski, US 2003) to *The Day the Earth Stood Still* (Scott Derrickson, US 2008) and *Star Trek: Beyond* (Justin Lin, US 2016) have depicted such swarm attacks by impressive CGI sequences – which, as a matter of fact, are also operating with SI (see e.g. Vehlken 2013b); fictional scenarios whose visual sophistication nonetheless might add its part to imagined futures like Scharre's.

In addition, some authors stress that different types of sensors could be distributed to different swarm members, a so-called heterogeneous group control (Economist 2017). This means that the functions of failing or eliminated UAVs can easily be taken over by other swarm members and the operational readiness of the Swarm UAS remains intact. Other explore their suitability as electronic warfare devices – e.g., as distributed beamforming platforms used for jamming enemy radar (see e.g. Kocaman 2008; Cevik et al. 2012), or as electromagnetic pulse weapons (Hammes 2016: 8). Moreover, Swarm UAS could serve as mobile minefields in the air, on the ground, and under water. Furthermore, their small size is seen as an asset: "With the advancement of radar and sensors in addition to on-going developments of counter-stealth technology, only systems at the micro, near-silent and ultra-low energy levels will have any chance of operating undetected." (Goh 2017: 46). And with novel types of nanoexplosives, the small payload capacity of Swarm UAS nonetheless could yield substantial destructive effects (for a compelling overview, see Hambling 2015: 209–241) – not unlike the bats of Project X, but this time, with a (or multiple) clearly defined vector(s).

However, if (semi-) autonomous Swarm UAS would be employed for force projection in such ways, this does not only intensify ethical objections like those already discussed in the context of existing drones or robot systems, like possibly automated kill decisions (see e.g. Suarez 2017). Various authors therefore call for the necessity to put the employment of such systems under international law and classify them as weapons of mass destruction, or at least ban them like land mines or cluster bombs (see e.g. Chamayou 2015; see Hambling 2015; see Hammes 2016).

And this, finally, brings us back to the clear-sightedness of Stanislaw Lem's essay: If not being critically discussed and regulated, scenarios could become realistic where the spatio-temporal intelligence of Swarm UAS could lead into a similar direction as he sketched it out in his futuristic essay:

> The greatest problem in the unhuman stage of military history was that of distinguishing friend from foe. This task had been accomplished, in the twentieth century, by means of electronic systems working on a password principle. Challenged by radio, a plane or an unmanned missile either radioed the right answer or else was attacked as an enemy craft. This ancient method now proved useless. The new weapon-makers again borrowed from the biosphere [...]. The nonliving weapon might imitate (extremely well) floating dust specks or pollen, or gnats, or drops of water. But under that mask lay a corrosive or lethal

agent. [...] Thus peace was war, and war peace. Although the catastrophic consequences of this trend for the future were clear – a mutual victory indistinguishable from universal destruction – the world continued to move in that fatal direction. It was not a totalitarian conspiracy, as Orwell once imagined, that made peace war, but the technological advances that effaced the boundary between the natural and the artificial in every area of human life. (Lem 1983: 34 and 38)

Thus, to conclude, the consideration of a possible significance of technologies which seek to exploit the particular "artificial nonintelligence" of SI and SR boils down to the interpretation of 'pervasion': With its promise of producing emergent solutions for routing, survey, or SMAVNET tasks SI and SR generate more efficient and sustainable methods of 'controlling' space; that is, in a mere managerial articulation of its meaning. However, as the military debate implies, it also portends a rather restrictive biopolitical and governmental downside. Of all things, it could be the bio-inspired tempo-spatial intelligence of Swarm UAS which is attributed – while interweaving natural phenomena and behaviors with technical networks – the risk of straightly clearing a path of regression to something like the Hobbesian 'natural state'. Only this time, in a media-ecologically enhanced version. As long as such scenarios are still speculative because of the infancy states of most of the technologies involved, and with regard to the topic of this issue of *Digital Culture and Society*, it may suffice to state that in the slipstream of current AI killer applications, it is the peculiar form of behavioral AI exhibited by swarm intelligence which no longer only governs the motion control of artificial agents in computer simulations or of robot collectives in unknown environments, but which might transform our understanding and control of environmental space as such.

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