Milling Swarm

An improved approach to large envelope precision machining.

Prepared for presentation to Electroimpact Inc.
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Abstract

Advances in laser tracking will enable small transportable modular units to completely exclude large installed one-off equipment from the marketplace for large envelope precision automation.

Large precision work pieces are common in the fields of transportation and heavy industry. Producing these work pieces currently relies on a combination of off-site large envelope machining and on-site precision assembly. These in turn require very expensive monolithic stationary capital in the form of large gantry milling machines, assembly jigs, drilling and riveting machines, and the like. Much of this equipment is single purpose. The development of multi-purpose transportable large envelope automation will radically affect the business environment of these sectors.

Ongoing improvements in laser tracking technology and equipment will make it feasible to locate small machines in space relative to their work pieces on a per-setup basis, using multiple setups to achieve the final result. This is the “swarm” approach.

Due to its many advantages, the swarm approach will rapidly and irrevocably replace sequential off-site fabrication with **parallel on-site fabrication**. Although this paper focuses mainly on large envelope milling, the swarm approach is applicable to many other industries, and many other processes.

As this paper was prepared for Electroimpact (a manufacturer of aerospace tooling and automation) examples applicable to aircraft are used thruought. However, these principles apply equally well to other large envelope precision automated processes.

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State of the Art

Aircraft are currently manufactured by moving components through a sequence of workspaces. Each workspace is largely dominated by single purpose tooling (tape laying machine, automated drilling and fastening machine, assembly jig, paint booth, inspection equipment, etc). The tooling itself often requires large stationary equipment for its manufacture (large milling machines, high capacity cranes, etc). This large tooling and automation cannot share workspaces, and is often single purpose. It is expensive to produce, difficult to reconfigure, and prohibitive to transport after installation. Therefore, much of the structure is prefabricated off-site and shipped in for final assembly.

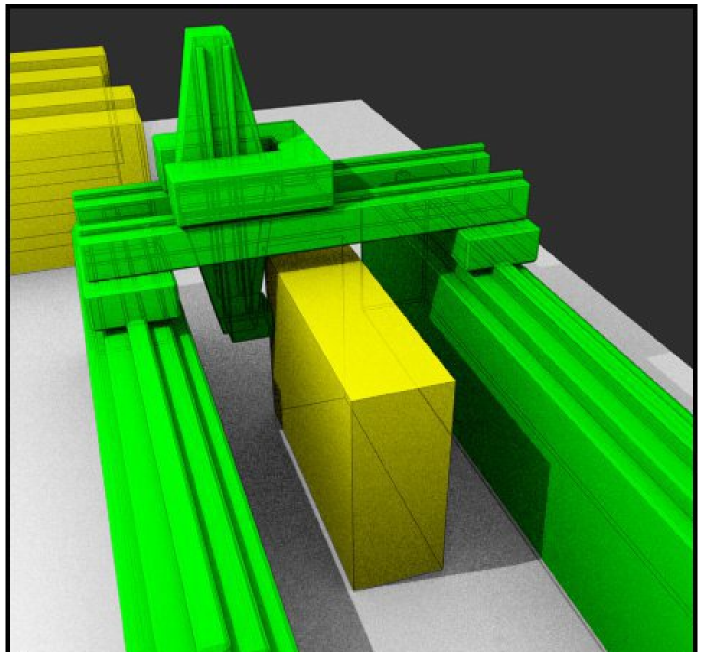

Figure 1: Gantry Mill

In order to verify a quality product, aircraft parts and tooling are nearly always inspected before shipping to the work site. This is necessary because it is prohibitive to fabricate and rework parts on-site (as outlined above). Once delivered to the final assembly location, both aircraft and aircraft tooling must be assembled precisely in order to achieve a satisfactory end result.

Monolithic Capital Equipment

A significant fraction of the capital investment required for aircraft manufacturing is sunk into large equipment, such as automated drilling and fastening systems and tape laying machines.

This equipment is large because single-setup operations are more reliable and accurate than multiple setup operations, and so the machine must have a working envelope larger than the work piece. Aircraft work pieces are typically large enough that a single machine which can enclose the entire volume is too massive to easily transport without disassembly. Because assembly after shipping is costly and time consuming, these machines are effectively non-transportable.

In addition, because the machine must be free to move through the entire volume, conflicts with other machinery are avoided at all costs. This results in automation with a single tool-point per work station, which directly limits production rate.

Machine setup and calibration is increasingly carried out with the aid of laser trackers.

Pre-ship Inspection

Because aircraft (and aircraft tooling) fabrication relies on such massive equipment, this equipment is often built or even stationed off-site. Lacking on-site equipment to perform similar functions, rework becomes prohibitive or impossible. Pre-ship inspection is critical to detect any flaws before the work piece leaves the site of the non-transportable automation. This inspection is often repeated when the work piece arrives at its destination, as damage during shipping is not uncommon.

Inspection is increasingly carried out with the aid of laser trackers.

Precision On-site Assembly

Because a precision product is required, components transported from off-site locations must be assembled using precision techniques. This requires further large stationary capital expenditure in the form of jigs and fixtures. These jigs and fixtures are often specialized and non-configurable in order to simplify operation and drive down tooling costs. This has the drawback that production line changes are not possible without large expenditure on retooling to adapt jigs and fixtures.

Assembly is increasingly carried out with the aid of laser trackers.

Swarm Machining

Laser trackers will become good enough to drive all fabrication, machining, and inspection on-site while eliminating precision assembly. This will, in turn, enable multiple small machines to work simultaneously on the same work piece.

This paper focuses on machining because large part milling appears to be the ideal initial application for this technology (along with swarm cranes). However (since drilling is a sub-set of machining) the principles apply equally to aerospace drilling and fastening, along with a number of other processes.

Overview

Swarm machining means employing many small milling machines do in parallel what one large machine would normally do in sequence.

Modular Swarm Units

Each swarm unit is a milling machine designed to be easily transported, secured, and operated. Because they are oriented by laser tracker after mounting, they need be only roughly positioned relative to the work piece, as long as the mounting is rigid. They are interchangeable in the sense that all units have standardized interfaces. That is, they have the same fit, form, and function. The actual structure of the unit need not be the same. In this way, units from different manufacturers are freely interchangeable.

Standardized Hardware Interface

Modular swarm units will be mounted to a rigid base, or to the work piece itself, using a three point mounting. This produces rigid mounting without introducing torsion. A mounting system with more than three points will necessarily deform the unit, which will require a complete unit re-compensation (with thousands of data points) in order to produce accurate results. In contrast, a three point mounting system introduces no deforming forces, and therefore maintains the validity of pre-existing unit compensation. Using this method, only three data points need be laser tracked to correctly orient the unit in part-space.

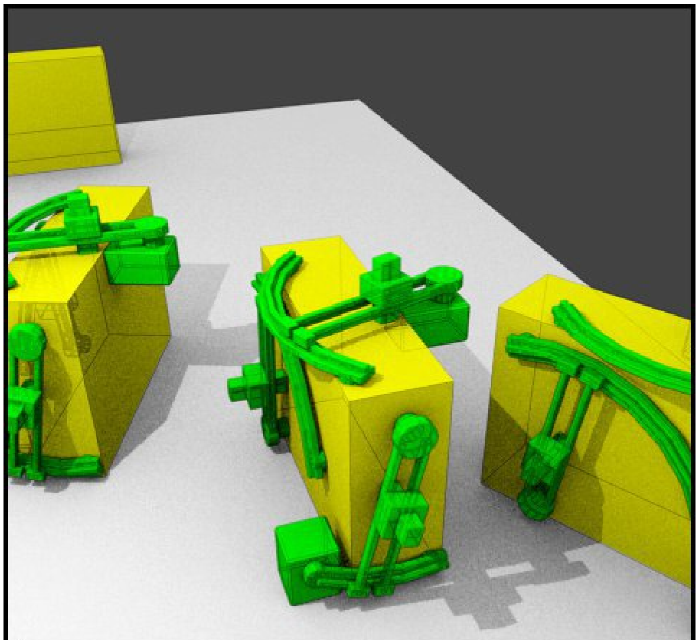

Figure 2: Swarm Mill

In addition to mounting, a standard power supply format should be specified. It is foreseen that electricity and pressurized air are likely requirements for unit operation. If possible, each unit should be adaptable to a broad range of electrical voltages, phases, and frequencies, as well as a broad range of pneumatic pressure, air quality, and humidity, in order to accommodate on-site conditions.

It is theorized that a spherical bearing clamped to a slot will provide the necessary mounting rigidity and configuration flexibility. Solid state invertors and pressure regulators and intensifiers will vastly broaden the acceptable range of power input. The specifics of the standard hardware interface should be determined by the Swarm Division.

Standardized Software Interface

Without built in artificial intelligence, modular swarm units must receive their operating instructions from an outside source. Because units are intended to be functionally interchangeable, a standard software interface is highly desirable. This interface should be somewhat secure (so that dangerous machinery instructions are not issued by accident or malice) as well as flexible (to accommodate unforeseen machine features and applications). It should also be an open format, so that anyone can produce compatible control systems.

It should allow communication of geometry both to and from the swarm unit, as the unit may be requested or required to perform inspection duties either exclusively, or during the course of its other tasks.

It is unknown at this time whether a suitable software interface of this nature already exists. Final specification should be the responsibility of the Swarm Division.

Unit Transportation

On-site machining is a central advantage of the swarm concept. Therefore, swarm units should be small and light enough to be transmitted via existing transportation networks without disassembly or special preparation. They should also be rigid and strong enough to be lifted by crane by any of their three standard mounting points. This will allow the owner or customer to easily allocate swarm units to the location of most profitable employment.

Unit Installation

The swarm concept assumes that each swarm unit is stationary relative to the work piece during operation.

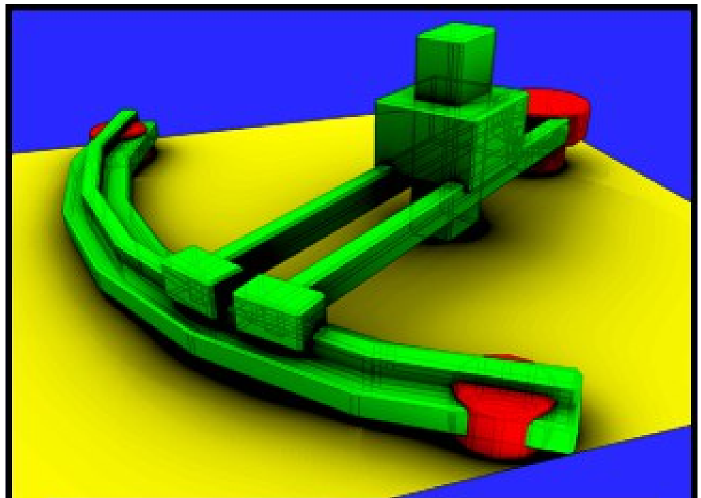
Figure 3: Swarm Unit

Work Piece Supported

The most straightforward method is to mount the swarm unit to the work piece itself. This method is preferred because it minimizes the load path loop length, thereby maximizing full system rigidity (which in turn directly improves vibration damping, machined surface finish, and total accuracy) as well as reducing the effect of differential thermal growth and mid-process work piece warp.

Work pieces which have an unsuitable geometry or material may be accommodated with the use of temporary work piece extensions such as brackets and standoffs. Because each swarm unit is post-mount located using laser tracker, these temporary mounting aids need not be of precise manufacture or positioning. They can be fabricated on-site using rough techniques such as welding or concrete casting. Securing the mounting aids to the work piece may be accomplished through a variety of methods including (but not limited to) bolt slots, suction devices, magnets, clamps, and adhesives.

Jig Supported

For work pieces too fragile or weak to support the weight of a swarm unit, a mounting jig may be employed. A jig is simply a larger more complete version of the mounting aids mentioned above, and thus the same principles apply. As always, load loop length should be minimized wherever possible.

Robot Supported

It is possible to use a swarm unit as a "tool tip" for large robotic automation. However, the costs, benefits, and implications of such employment fall outside the scope of this paper. The Swarm Division should investigate this concept.

Unit Operation
Once in place, the swarm unit must receive operation instructions and coordinate data, and then perform the required work.

Programming
A swarm unit should be easily programmed either manually, or with the aid of software. It is desirable that a swarm unit will be able to self-determine a tool path based on given imported geometry specifications, as well as automatically link into a local swarm ad-hoc network to coordinate with and receive data from nearby machines, but it is unknown at this stage if these are feasible requirements.

Shoot-in
After mounting, but before beginning work, a swarm unit must perform a self-orientation procedure. This procedure will likely consist of gathering tracker data at four positions in the corners of the machine envelope, in order to secure a strong baseline. In order to reduce tolerance stack up, it is preferable that the laser tracker be mounted directly to the swarm unit and shoot in to tracker ball nests directly on the work piece. If this is infeasible due to line of sight issues or tracker setup time, a remote tracker may shoot in to both the work piece and the swarm unit itself.

Run
Once the swarm unit is secured in place and oriented correctly to the work piece, it may immediately begin work. Swarm units are expected to have exclusive work zones, but intra swarm communication and coordination may prove beneficial (as with a pair of units coordinating to perform rivet squeeze or collar swaging).

Advantages
Swarm fabrication is expected to drastically increase fabrication flexibility, boost production rate, reduce floorspace requirements, slash shipping costs, and speed inspection.

Transportable
Because swarm units are easily transported, they can be employed at or very near the final point of use. This greatly aids both product manufacturing, and product field repair.

Ease of transportation also allows the OEM to transport malfunctioning units to their facilities for service instead of sending repair teams out to the field.

Configurable
Because swarm units are purpose-agnostic, they are easily reconfigured for a variety of tasks. Unlike large single-purpose tooling, swarm tooling is inherently future proof. In addition, the modular nature of the units allows dynamic allocation of automation resources.

Unlimited Envelope

The effective working envelope of a swarm is limited only by the long-range accuracy of laser trackers. Even now, this range far outstrips even the largest mills. By chaining laser trackers, the swarm envelope becomes effectively unlimited.

Parallel Machining

By limiting their exclusion footprint to the smallest zone possible, swarm units are easily able to work in parallel. The total production rate is still limited by the slowest machine, but because each machine is working in a much smaller envelope, the time to completion will be much reduced.

Elimination of Precision Assembly

Because swarm units are transportable and small, they are capable of producing critical features after final installation. This creates the possibility of machining precision features into a part after it has undergone shipping, assembly, and settling, resulting in a superior end product. Because this largely eliminates the need for precision assembly features such as highly flat and smooth surfaces, precisely positioned dowel holes, and keyways, products designed for manufacture with swarm technology will be cheaper to manufacture.

Synchronous Inspection

Because laser trackers form the foundation for both modern part inspection and swarm technology, it is foreseen that part inspection will be carried out by sensors onboard swarm units in concert with their work piece modification actions. This combination of work piece forming and quality checking will increase manufacturing rate, as subsequent quality checks need only verify the accuracy of a few points of data gathered by each swarm unit.

Critical Technologies

Swarm machining relies on two new technologies: Laser trackers, and control software. Specific thresholds for swarm feasibility are currently unknown. It is suspected that swarm technology is already feasible for adoption for the specialized applications of Electroimpact, and will be feasible for widespread industrial adoption in the near future.

Laser Tracking

In order for swarm technology to capture the market, laser trackers must be:

1. Accurate enough to locate swarm units within acceptable tolerances.
2. Reliable enough to consistently provide correct data, even under non-ideal conditions.
3. Easy enough to use that training and retaining competent operators is not cost prohibitive.
4. Inexpensive enough that they do not make swarm unit employment cost prohibitive.
5. Robust enough to withstand industrial environments for long periods of time.
6. Common enough that their repair, maintenance, and/or replacement is quick and reliable.

Spatial Control Software

In order for swarm technology to capture the market, the required spatial control software must be:

1. Sound and proven enough that clients will trust the machines to correctly perform their tasks.
2. Inexpensive enough that licensing fees are not cost prohibitive.
3. Easy enough to maintain that clients can be assured their equipment will continue to be controllable for the foreseeable future.
4. Transparent enough that third parties can provide control software and interface translations of existing NC programs.
5. Forward- and backward-compatible enough that control programs will not become invalid due to foreseeable future releases.

Applications

In addition to milling of aerospace tooling, swarm tools are projected to be profitable for employment in several other fields.

Transport

Large vehicles are a ripe market for application of swarm manufacturing.

Aerospace

Airplanes and rockets are currently limited by transport infrastructure required to move sub-assemblies to the final assembly area. By aggressive application of swarm technology, aerospace vessels could be manufactured from raw materials on-site, removing many design constraints and resulting in more efficient designs. This would also decrease transport costs (since raw materials are cheaper to transport than sub-assemblies), increase floor space utilization (because swarm units have a small excluded volume, and occupy no permanent location), and improve schedule (because swarm units can work in parallel).

Mining

The largest terrestrial vehicles in the world are used in the mining sector. Swarm techniques could deliver full sized equipment to currently inaccessible locations by on-site fabrication and machining. This would also reduce mining impact on the environment, as access roads would need only accommodate normal sized vehicles to transport parts and materials, instead of the much larger mining vehicles. Swarm tools would also improve maintenance by providing on-site precision repairs.

Marine

Many large marine vessels require work-specific modification for a variety of tasks. Swarm machines could be kept on-board and used to make in-voyage modifications and repairs.

Although transportation of sub-assemblies is not generally an issue for marine fabrication, it is suspected that swarm techniques could be put to good use in marine structure manufacturing. The use of remote operated submersibles for oil platform inspection and repair demonstrates that there is a demand for automation. Swarm techniques may be applicable in these areas.

Heavy Industry

Large scale industry could benefit from swarm techniques, specifically the foundry and petro-chemical sectors.

Petro-Chemical

Oil refineries are constantly undergoing changes to process equipment in hazardous environments. Swarm machines would provide the ability to make precise changes to equipment, while keeping operators at a safe distance.

Foundry

Steel mills and refineries employ large, heavy equipment. When they require maintenance, it is often impossible or prohibitive to access precision machine tools with a sufficient volume to address the entire work piece. Swarm machines could be employed to precisely modify and repair heavy industrial equipment without removing such equipment from the process line.

Construction

Modern construction deals with large structures. Although the numerical accuracy required is much less than that of airplanes, the total envelope is also much larger, making assembly accuracy a pressing concern due to tolerance stack up.

Energy

Power plants and wind turbines are largely fabricated and machined off-site. Swarm techniques could allow these large and expensive products to be assembled on-site from raw materials. This case bears many similarities to the heavy industry and transport examples.

Infrastructure

Roads, bridges, tunnels, pipelines, and transmission lines all pass through remote and difficult to access areas. While on-site fabrication is already the industry standard, access to large envelope precision tools will provide advantages for both design and execution.

Low Margin Markets

Once swarm machines are firmly established in high margin markets, it is likely that they will see adoption by individual scale markets as well.

Static Shop Use

Job shops will not go away. They will likely adopt swarm machines due to their broad availability, and the option of taking contracts on large projects.

Personal Use

Swarm machines may, of course, be employed individually by individuals. Because of their easy transport and setup, it is projected that there will be a market for these machines around the same time that laser trackers become cheap and robust enough to qualify as consumer equipment.

Related Swarm Concepts

In addition to the milling example above, swarm machines are a suitable platform for the automation of a variety of precision tool-point manufacturing techniques.

Subtractive Swarm

The example of milling is a subtractive technique. EDM and linear cutting are other possible examples.

Swarm EDM

Because of the extraordinarily “steady hand” required by electric discharge machining (EDM), it is somewhat unique in being a subtractive technique almost exclusive to automated tools. It will probably see early use for specialized tools designed for part rework. However, because the tolerances for EDM are generally an order of magnitude tighter than those of machining, it is not likely that swarm EDM will replace static EDM equipment. Even so, the vastly larger envelope offered by swarm techniques will enable employment of EDM in previously infeasible situations. On-site EDM swarm units will likely see small scale adoption in applicable fields.

Swarm Cutting

Laser cutting and water jet cutting are ideal swarm candidates. They require steady tool point feed rates (making them generally unsuitable for manual operation), are used on large sheets, and are rate dependent for profit. Multiple swarm units operating in parallel could boost production rate while reducing equipment footprint and insuring against downtime by eliminating single points of failure.

Positional Swarm

Swarm units can be used to position parts, or change their shape.

Swarm Jig

If a precision jig is required, it may be built from swarm units anchored to a roughly fabricated frame. The jig would then be fully configurable, easy to disassemble and transport, and inexpensive to set up.

Swarm Forming

Rivet forming is currently accomplished with either inertial techniques (EMR) or large structural techniques (D-frame squeeze riveting). EMR has the advantage of not requiring a large rigid structure to transfer forces. D-frame squeeze riveting has the advantage of precision and repeatability. Swarm riveters provide the advantages of both techniques by employing small inexpensive units with squeeze rivet capability in a large effective working volume.

Bending, forging, drawing, and shaping are generally performed by large stationary automation tools. However, this precludes shaping very large pieces, or shaping pieces in the field. Swarm units could be employed to form extremely large sheets perhaps for use in architecture or infrastructure, as well as in-place forming for precision installation, press fit, or repair.

Swarm Crane

Cranes pose a critical point of failure for many industrial processes. Crane units are generally controlled directly, which makes it difficult to precisely control the motion of the load. They also require spreader bars and specialized lifting jigs to lift large, irregular, and fragile loads. A synchronized swarm of small crane units could lift loads of arbitrary size and geometry. In addition, they could arbitrarily re-orient loads during a lift, eliminating the need for turn-over jigs. Multiple swarm units also eliminate the single point of failure posed by large cranes, thus improving reliability.

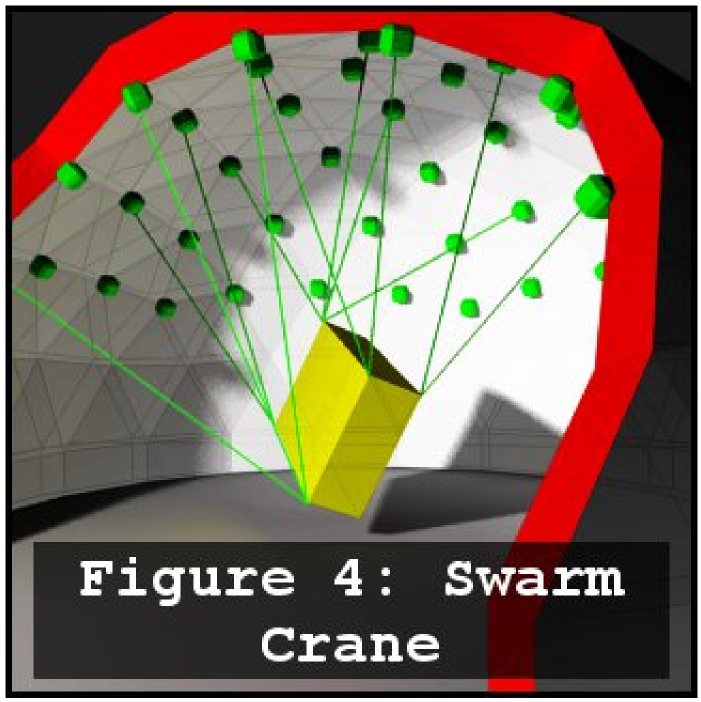
Figure 4: Swarm Crane

In addition, many industrial buildings are designed around cranes. By removing this design criteria, buildings will naturally take the shape of domes, which are more rigid and better suited for maintaining internal environmental conditions. This, in turn, will allow vast internal volumes free from supports, which will synergize with on-site monolithic manufacturing of large products such as aircraft.

Additive Swarm

Swarm units are easily adaptable to additive fabrication techniques.

Swarm Welding

Welding quality relies heavily on operator consistency. Automated welding systems already exist, and produce extremely high quality welds, but are generally bulky and stationary. By adapting swarm technology to welding, high quality welded joints may be produced anywhere in the world for relatively little cost.

Swarm Printing

3D printing technology is currently much hyped. While it is certainly feasible to perform 3d printing with swarm units (and, indeed, most 3d printing units are small enough to be easily converted into swarm printers) it is unclear if there is advantage to be gained by integration with laser trackers at this point. The possibility remains however.

Alternative Emerging Technologies

The primary competition with swarm techniques for manufacturing low volume large scale artifacts is (and will likely always be) manual human craftsmanship. Because each individual human may be seen as a highly configurable swarm unit with capacity for advanced visual tracking, unparalleled safety, ad-hoc audio network formation, local coordination, and a host of other beneficial features, this may be taken as a confirmation that the swarm concept is, fundamentally, sound.

The main competitors with laser trackers for large volume precision spatial position measurement are temporal techniques such as GPS and laser interferometers. While these technologies may outstrip mechanically encoded laser trackers, the swarm applications remain the same. Thus, far from being a threat to swarm techniques, alternative spatial measurement techniques strengthen the case for swarm technology adoption and development.

Swarm technology is not foreseen to displace current mass production techniques for high volume goods. It is therefore not likely that the automotive and consumer manufacturing sectors will see benefit from adopting swarm technology.

Conclusion

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Thank you for your consideration of these matters. Please feel free to contact me if you desire any further elaboration on the content above, as well as its derivation and implications.

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