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Pros and Cons of Industrial Robots in Additive Manufacturing

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Abstract

Advances in non-planar, multi-axis, and hybrid material extrusion additive manufacturing techniques increasingly demand active nozzle orientation control. Industrial articulated robot arms are commonly implemented for repetitive manufacturing tasks and these arms are becoming a common choice of motion platform for additive manufacturing given their ubiquity and flexibility. Here we explore the pragmatic benefits and challenges of using industrial robotic arms for extrusion additive manufacturing. While robotic arms from established manufacturers are highly capable, recent offerings are more easily integrated and safer, while providing the same or improved capabilities as the more traditional models.

1 Background

Planar, gantry-type material extrusion additive manufacturing has become commonplace in homes, labs, and businesses of all levels. This democratization allows designers in many industries to easily produce prototypes and increasingly promotes the creation of complex and multi-material parts that could not be produced through subtractive manufacturing. These gantry systems are mechanically simple and often constructed using off-the-shelf parts. However, as adoption progresses from prototypes to functional final-use parts, surface quality and strength improvements can be made by moving to non-planar printing techniques. These improvements require more degrees of freedom (DoF) than gantry systems can readily provide. Here we present the practical benefits and challenges of using typical industrial robotic arms in extrusion additive manufacturing based on observations in working with real-world robots in an academic research environment. Actuator limitations and form factors as they apply to additive manufacturing, and their benefits and detriments are discussed. State-of-the-industry suggestions, observations, and possible alternatives for new projects are made based on market offerings from companies attending an international robotics tradeshow in 2024.

ASTM (formerly known as the American Society for Testing and Materials) defines material extrusion as the “additive manufacturing process in which material is selectively dispensed through a nozzle or orifice” [1]. This type of additive manufacturing (AM) has been referred to as Fused Filament Fabrication (FFF), Fused Deposition Modeling (FDM, a trademarked term), and the ASTM term Material Extrusion (MEX) [2]. While many hobbyist desktop 3D printers use MEX Cartesian gantry systems, these systems have known limitations in terms of surface quality and strength [3–5]. Pires et al. [6] reports that these often stem from lack of nozzle orientation control and planar layer design which requires the use of sacrificial support material. Removing said material can leave surface defects and increase waste and production time. This often leads designers to create part designs that avoid the need for support material, further limiting what can be produced [6].

1.1 The Active-Z Solution

Extending extrusion motion beyond the XY plane and into the Z dimension can potentially eliminate the need for support material. One method to bypass supports is using radial bottom layers that grow similar to tree rings [7]. Unfortunately, this technique decreases bottom surface finish quality but can be utilized by stock gantry printers. Another method of avoiding the need for supports is to slice the object such that the layers are slopes capable of supporting themselves. Kubalak et al. explored this concept using multi-planar layers [8]. The exact design of the layer curvature is chosen by the designer and/or by the slicing algorithm but is hardware-limited by nozzle orientation and maximum layer slope. Surface smoothness diminishes as that limit is reached [3, 9, 10]. Roughness is created by the nozzle tip corners scraping the previous layer or freshly deposited material. This surface damage may lead to poorer inter-layer bonding, increase the number of crack initiation sites, and decrease the aesthetic quality of the part. Mackay et al. suggest that this may also lead to inconsistent extrusion bead profile, layer thicknesses, surface smoothness, and inter-bead bond area [2].

The more limiting factor with Active-Z printing is design geometry limitations. Although Active-Z allows for increased design freedom over planar slicing/printing, the printable geometry is still limited and the surface finish of downward-facing surfaces may suffer. To utilize the full geometric design space available within modern digital design tools such as SolidWorks and nTopology nozzle orientation control is required. This is necessary not only to fabricate the geometry but to do so in a manner that produces quality parts (e.g., strong and accurate) [11]. Even with pushing orientation-locked systems to their physical limits using approaches like Active-Z, these systems are often limited to building prototypes and demonstration units for quality reasons.

1.1.1 Full Nozzle Orientation Control

In order to meet the goal of producing quality, functional, end-use parts using MEX, true 6+ DoF nozzle control is required. This allows for both position and orientation control of the nozzle orifice relative to the build surface. Pires et al., Khurana et al., Kubalak et al., and Huang et al. all report that nozzle orientation if changed from being locked normal to the build platform (the Z direction of the build plate), these design limitations would be greatly alleviated. They also report that nozzle orientation relative to the surface being printed on is one of the factors that drives bonding between beads of extruded material [3–6, 9]. Most parts fail at the layer division lines, even with promising advances in increasing layer-to-layer bond strength including selectively reheating entire layers [12] or microwave heating carbon nanotubes at the interfaces to increase bonding [13]. Rajpurohit et al. and Kubalak et al. showed that parts with layer lines parallel to the applied tensile load were stronger than those with layer lines perpendicular to loading. This shows that bead tensile strength tends to exceed intra-layer bond strength in traditional planar MEX parts [8, 14].

Several actuator hardware configurations meet the requirements of producing active nozzle orientation. These include highly adaptable robots of the articulated arm, SCARA, and delta types. Another option is higher-stiffness 3-axis gantry systems with additional degrees of freedom provided by a tilt/turn table. This gantry-plus-table configuration may come at a lower price but with added integration complexity or lower reliability. Each of these solutions comes with drawbacks, however. Gantry systems, including hobbyist desktop MEX printers, are kinematically simple but require rails to be constructed enclosing the entire build volume and thus always take up their maximum space. SCARA robots (originally known as "Selective Compliance Assembly Robot Arms" [15]) are lightweight but unable to orient the end effector (tip of the robot where a MEX nozzle could be mounted) and thus are limited in the same way a gantry system is. Delta robots keep most of the robot mass in a stationary body while lightweight limbs move the end effector. While these robots can be extremely fast due to the low mass of their limbs, they cannot achieve the required magnitude of rotation control without additional actuators. Finally, articulated robotic arms with serial actuators commonly seen in robotic welding work cells tend to be heavier than the others, leading to greater momentum and vibration effects [16].

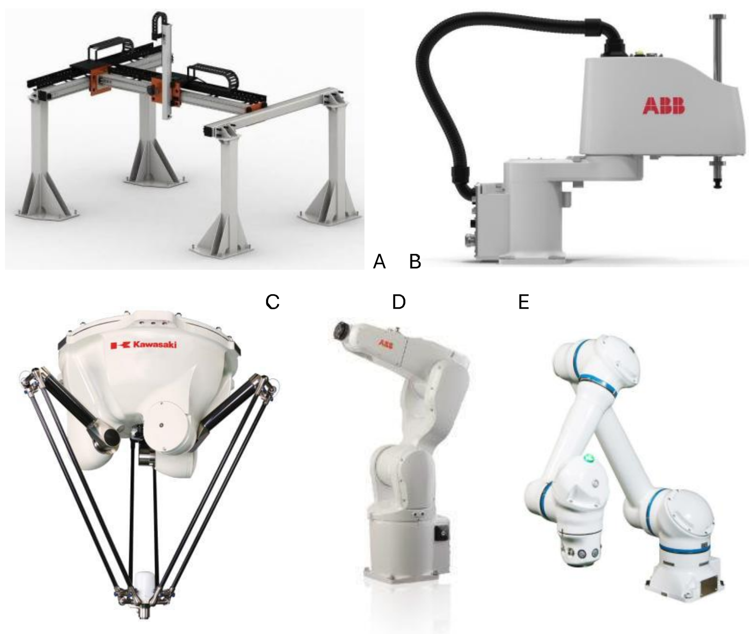

Figure 1: Common varieties of robots in industry, each with a rated payload capacity of approximately 6kg. A) 3 DoF gantry system, B) SCARA, C) delta, D and E) industrial and cooperative articulated arms respectively. Images via Appendix A: 61 - 65.

Additionally, these actuator types may be composed of proprietary (closed) hardware and software that are difficult to adapt for AM applications. The SCARA and delta industrial robots utilize the same or similar closed control environments as the articulated ones but require the additional complication of integrating at minimum one new axis (for nozzle orientation). As most of the mass of a gantry, SCARA, or delta robot is in the stationary frame, these systems can change direction more quickly. This is a benefit while trying to print sharp corners but this high speed also comes with the concern for human safety and thus requires safety guards. One unifying feature of all these robot types is that each of these systems is sold with controller hardware usually running proprietary algorithms. These algorithms aim to negate unwanted motions such as actuator vibration within a factory automation setting [17]. While these types of industrial robots may have similar positional capabilities, most cannot maneuver around objects and approach parts from different orientations. Functionally, this means that parts must be printed exclusively in ascending Z order. Gantry, SCARA, and delta robots also require an additional structural framework, as they must be mounted above the build plate. This is in contrast to articulated arms that can be positioned beside (or above) the build plate and have a joint configuration that allows them to print in almost any position and orientation while avoiding collisions. Summarized in Figure 2, it becomes clear that the best architectural fit for robotic additive manufacturing is an articulated robotic arm with six or more degrees of freedom.

	Gantry	SCARA	Delta	Articulated
Typical DOF without add-ons*	3	4	3	6
Bottom of Cantilever Access	X	X	X	✓
Frameless	X	X	X	✓
Mechanism Inertia Rating (1-3)**	2	2	1	3
Mechanical Complexity (1-3)***	1	2	2	3

*Additional degrees of freedom (e.g. tilt/turn tables) may be needed to reach the total of 6 DoF required for full non-planar printing.

**Lower is better to minimize vibration and maximize quickness of motion changes.

***Lower is better from a failure and maintenance perspective. Installed cost generally increases with complexity.

Figure 2: Comparing four major types of robots. High-level details of actuators found in industry and factors relating to their use in additive manufacturing. Highlighted cells indicate best rank in that category.

1.2 Importance of RoMEX

Robotic Material Extrusion (RoMEX) presents substantial advantages over traditional material extrusion systems, particularly those using gantries. RoMEX systems are defined by their six serial axes and a heated extruder nozzle. By utilizing more than three degrees of freedom, these systems are no longer constrained to planar or Active-Z printing, meaning support structures are often no longer needed, saving time (printing and post-processing) and material. RoMEX allows for curved, conformal layer printing, potentially significantly improving the structural integrity and surface quality of printed parts [11]. The nozzle orientation capabilities allow inner structures to be printed and encased by a shell of different print parameters, even if overhangs are present [9]. Using a finer layer shell over a coarser and faster printing core can reduce print time by approximately half [18]. Another strength of this printing technique is its ability to do mid-print component integration. This simplifies later assembly and amplifies the effect of part consolidation commonly touted in AM. Complex shapes can even be integrated by using shape converters that ensure proper encapsulation while maintaining print strength [19].

By combining non-planar and conformal printing techniques, large parts need not be printed monolithically but can instead be printed in modular sections with one smaller printer. Bhatt et al. state that this is in direct contrast to gantry printers that must envelop the entire part throughout the process and thus are larger, require greater infrastructure, and are higher cost when printing at the architectural scale. The ability to print modularly is also why mobile RoMEX systems have been proposed for printing concrete buildings [11].

Robotic AM systems like those used in DED (Direct Energy Deposition, a hot metal deposition process using an articulated arm robot akin to RoMEX) have been shown to be smaller and 30 percent cheaper than their gantry equivalents [6]. However, the serial nature of joints in articulated arms leads to less stiff systems from base to end effector. Pires et al. indicate that this effect is more important in the subtractive manufacturing space than the additive one as the force applied on the end effector from cutting tools is significantly higher than from an extruder [6]. This lack of rigidity has historically led to RoMEX and DED systems that are slower than similar gantry-based systems when printing planar layers. Print speeds increase significantly when using the curved layer techniques enabled by RoMEX. Speed, surface finish, and multi-material capabilities may all be further improved by utilizing multiple arms, potentially mounted in different orientations.

2 Robots in Material Extrusion

This work aims to summarize the findings in existing literature, but more importantly, describe the real-world experiences of the authors implementing these machines in RoMEX research. Specifically, the pros and cons, expected and experienced, of using the robot arms sold to the industrial automation sector for use on dull (i.e. repetitive), dirty, and dangerous tasks. The most important criteria to consider when picking any actuator for a RoMEX application are the ability to control the position and orientation of the nozzle, reach, payload capacity, speed, accuracy, and ease of integration.

A longer reach corresponds to a larger build volume, potentially allowing for the production of larger parts. While payload capacity is important, payload ratings beyond 10 kg are likely excessive for most polymer RoMEX applications at the current scale. Robot joint speeds directly correlate to print speed, but as high print speeds can lead to print defects and poor layer adhesion, maximum robot speed beyond a certain threshold is less meaningful. It should be noted that robots cannot achieve maximum speeds under max payload conditions. Accuracy is important for part fidelity, but as articulated robot arms have historically been designed and used in repetitious tasks, they tend to emphasize repeatability over first-run accuracy. In RoMEX, most robots require some level of software interfacing for working with all but the most basic external systems. Cost (or equipment availability) is a major driving factor in these projects. Price varies widely between users based on negotiated prices, exact requirements for their application, and market demand. Few manufacturers have set list prices publicly available. These factors play into deciding which robot type, model, and brand is the best fit for a given project.

2.1 Pros: Strengths of Industrial Robots in RoMEX

RoMEX applications offer several advantages over MEX systems using a gantry system. Most prevalent is the ability to control orientation in addition to nozzle temperature, position, and feed rate. Future adoption of RoMEX systems likely depends on increasing system autonomy and ease of use [20]. Another advantage of articulated robotic arms is their compact installation size compared to other actuator types [6]. These robots are highly versatile and capable of adapting to a wide range of requirements, including component insertion mid-print and print inspection.

The adaptability of modern robotic arms makes them a cornerstone of industrial automation, capable of repeating complex motions that previously required human operators. The third-party robot programming software company RoboDK highlights this precision; “With RoboDK you can calibrate 6-axis robot arms and obtain accuracies up to 0.050 mm for small robots and 0.150 mm for medium-sized robots. The accuracy you can obtain after calibration highly depends on the robot model and your setup”[21]. This precision is important in RoMEX applications, where robot accuracy becomes part geometry. This accuracy is only obtained after lengthy calibration in a strictly controlled production environment.

2.1.1 Commercial Availability

This is not the first work to conclude that articulated arms best fit the requirements of RoMEX applications. Speed3D, the producer of cold spray robotic AM systems, has already adopted articulated robots for producing near-net-shape parts and for repairs [22]. Massive Dimension utilizes an ABB industrial robot (behind guards) as part of their RoMEX work cell [23]. The robot manufacturer ABB produces an add-on for their programming software RobotStudio called the 3D Printing PowerPac designed to create planar robot motions from hobbyist file types [24]. It should be noted that these systems run a static program designed ahead of time, without live external feedback. Although not a hardware manufacturer themselves, Ai Build offers software to generate tool paths and monitor prints using equipment from a number of the companies listed here [25]. These companies each share that they have also chosen to base their RoMEX designs around articulated robot arms.

2.1.2 Ubiquity

Over the past few decades, the demand for cheap and capable industrial robots for applications like assembly automation has led to the growth of companies both large and small. These robots usually represent a sizable capital investment and their current form came to prominence in the 1980s [26] and are now common sights in many manufacturing environments [27]. This ubiquity means that in settings where capital is limited (such as startup companies and research institutions), robots are often purchased in a used condition or repeatedly repurposed. This has begun to change with newer companies looking to disrupt the market by offering new features or lower costs.

As sales and market share data are difficult to obtain, this work classifies manufacturers according to the number of articulated arm robots offered in their catalogs. Specifically, companies were divided into three categories: those offering 20 or more models, those offering between 20 and 5, and those offering 5 or less. These groups are referred to here as large, medium, and small manufacturers respectively. The robot counts used for categorization excluded specialized configurations of the same robot model. Common specialties include cleanroom, paint, welding, or extended reach versions, often distinguished by model numbers with suffixes. Only base models are counted for this total (e.g. Yaskawa GP8 and GP8L count as one). Section 3.2 discusses more similarities and differences between these categories.

2.2 Cons: Drawbacks of Industrial Robots in RoMEX

While industrial robot arms are ubiquitous and capable of performing the active nozzle control needed for curved-layer RoMEX, they do have hurdles to overcome for implementation. Software integration, real-time control, hardware limitations, and manufacturer support are all potential roadblocks in using these systems. For example, industrial robots are typically not well suited for small motions (less than 1mm) [28]. These arms are utilized for highly repetitive motions where a human operator can only make adjustments during the programming phase. The result is a motion system that has high repeatability but low first-run accuracy [21]. These systems also may show communication queue problems including shutdown due to command overload [28], lack of predictable tool tip velocity [29–31], as well as difficulties establishing communication to and from the robot controller [32].

2.2.1 External Software

Many of the problems encountered in implementing industrial robots for non-repetitive tasks such as MEX printing, arise from the closed nature of their control systems. This work utilizes the authors' experience with an ABB IRB 140 and a KUKA LBR iiwa 7 r800. Both of these manufacturers require that all programs (in addition to add-ons and controller firmware) be uploaded exclusively from their proprietary software. In both company's programs, only basic functionality is available without an active license. The user cannot send live commands to the robot, even with a license, due to software limitations. It is assumed that this functionality is limited for safety reasons given that these robots lack environmental awareness. This means that in order to manually reposition the arm, an operator must do so from the interactive teach pendant attached to the controller. Multiple levels of safety must be met before running a pre-written program. Namely, the program must first be written and uploaded through licensed software. Then, the controller must be set to the correct state using a combination of the teach pendant and control cabinet buttons. Finally, once all safety enclosure doors are engaged, the program may be started from either the teach pendant or desktop software. Safety is achieved by ensuring humans remain separate from a moving robot at all times.

Industrial robots have also typically been produced strictly to run static programs repeatedly for a long time with little maintenance. This results in low downtime in a manufacturing environment but also minimizes users' ability to interface with external systems and accept input, sensor and otherwise. The Robot Operating System (ROS) is an open-source robotics platform used to coordinate multiple independent sensors, actuators, and software agents. Some robot arms themselves are controlled internally by ROS [33]. However, many of the industrial robots from the larger manufacturers, including both ABB and KUKA, lack official support for it. While some community developers have made contributions to connect ROS to robot brands like KUKA and ABB, these contributions do not always allow full access to robot commands or sensor data in ROS. Some brands unlock this feature through the purchase of a software add-on [34, 35].

In addition to proprietary desktop software, brands provide unique (and often closed-source) controller firmware. An application called Sunrise Workbench serves as the KUKA robot controller firmware. This application runs on top of a version of Microsoft Windows running on the robot controller itself [36]. ABB's equivalent is RobotWare (not to be confused with RobotStudio) which has a more basic interface. In industrial automation, this type of firmware is usually installed only once, and with a small number of static user-written programs. The start of these programs may be remotely triggered by a programmable logic controller (PLC). Both the ABB and KUKA robots have their respective programming languages in which programs are written. The ABB language, RAPID, is similar to C while KUKA uses JAVA. Some of the modern versions of these programs offer graphical programming options [36]. Greater system integration can be made difficult by closed-source firmware as most do not offer common 3rd-party software interfaces such as Python. These difficulties are only exacerbated by manufacturers requiring the purchase of features individually. This includes the firmware modules PC Interface from ABB and Fast Robot Interface (FRI) from KUKA which are needed to communicate remotely with their respective robots at all [37].

2.2.2 Command Streaming Techniques

While static, human-adjusted programs are sufficient for repeated pick and place, painting, and welding applications, additive manufacturing has different requirements. One of the strengths of AM is that each part can be customized, which is especially helpful for low-production runs. Usually, every layer of a part is different. This, in combination with the limited computational and storage resources on some robot controllers, means that external commands often need to be sent to the robot. Either in batches or one by one, streaming commands allow for command queues and external sensor data to be utilized, which many traditional robot controllers are not readily able to do.

Additionally, with the push into Industry 4.0 and the Internet of Things, an increasing number of robots offer network connectivity. While this has its own security concerns in terms of remote control, retrieving robot or end-effector data is valuable. Integration is effectively prevented by complications in interfacing with traditional industrial robots. Research-focused offerings from smaller manufacturers are more likely to offer out-of-the-box software integration options while established companies are likely to focus on safety through denial. Connection configuration to a robot also differs significantly across models and brands. While some readily interact over a network through common message types without much setup, others require configuration files to be manually transferred between host and client (robot controller). Even for robots on mobile platforms like the KUKA LBR used here, systems are often limited to one-to-one connections. Both ABB and KUKA robots have this limitation by default which increases the difficulty of collaboration between multiple arms and outside systems.

Methods for overcoming these communication challenges have been previously proposed. Although many robots face these issues, the following sections outline the four solutions found in literature as they apply to the ABB IRB robots in use by the authors. Badarinath et al [28, 29] showed the ability to convert tooltip speed to an analog voltage output. They then used external equipment to adjust the flow rate of their material extruder based on that value. This option is prone to electromagnetic noise, digital conversion errors, and latency both in the robot controller and in the external system. This method also suffers from a potential lack of fidelity depending on the scaling factor chosen for the voltage. The ability to output speed as an analog voltage is predicated on not only the robot controller software but also on the purchase of an additional input/output (I/O) hardware module sold by ABB. This module may also be required to use a similar digital system for outputting a single value from the controller.

The second workaround transfers a single value, as a binary number, by encoding bits as high/low states (representing 1s and 0s) across multiple controller digital outputs concurrently. This requires multiple digital I/O channels and may introduce additional conversion latency on either end. Consisting of digital signals, the transmitted value is less prone to outside electrical interference. Both the single analog voltage method and this one using multiple digital channels are only capable of communicating a single value at a time. Neither of these methods is capable of rapid communication of multiple values on the same channel.

The third known method of communicating with a robot controller is the Externally Guided Motion (EGM) add-on from ABB. EGM adds RAPID commands to establish bidirectional communication with an external device including move commands and joint positions [38]. This module does however require both purchase and elevated user rights for installation on physical controllers (i.e. outside ABB RobotStudio). These elevated permissions may not be available if repurposing an existing robot. This module is advertised as having 4ms response times [38], likely referring to communication rather than robot actuation times. As with other types of network communication, configuration can come with its challenges regardless of the robot brand. Modules such as EGM from ABB or FRI from KUKA are not common additions. As such, community support can be sparse, with users left only with a syntax reference guide. In addition to purchasing the modules themselves, additional training may be purchased. Third-party software interfaces such as the one from PickNik Robotics have been built on top of EGM in order to make it easier to implement even at the cost of command streaming functionality [39]. Note should be made to differentiate Externally Guided Motion (EGM) from ABB's Robot Web Services (RWS) which also allows for some level of communication using XML and JSON formats over a REST web API [40]. The use of RWS has not been explored as part of this work but may be useful for users already working with those formats.

A fourth communication option is to utilize web sockets. Although controller ports vary, most support TCP/IP socket communication over Ethernet. For example, this method is used in EGM, RWS, and to connect with programs like RobotStudio. However, as documentation is highly technical and difficult to locate, community use of this method has been restricted. As this method does not natively support passing motion commands to an ABB robot, users have tried to overcome this limitation by sending these commands in alternative ways. The RAPID language manual states that this method supports two main data types: strings (up to 80 characters), or bytes/byte arrays (up to 1024 bytes) [41]. Users have converted position and joint values to raw byte data that is then transmitted and stored as a user variable and reconverted in a move command execution loop [32]. Not only is communication size limited, but this method also adds non-negligible computation overhead, increasing latency.

A more polished method of this socket-based communication method is employed by RoboDK. This take on the socket method has users install and run a provided RAPID program on the controller (no elevated permissions required) to listen for and execute either TCP/IP socket messages or serial commands. Using this method, the RoboDK desktop app can communicate bidirectionally with the controller, including sending movement commands and reading joint positions [37]. This program is able to act as a bridge between outside software such as Python and the robot itself. The limitations of this digital framework, including behavior concerning command queues (latency, maximum size, effect of overload) are still being characterized, but impacts on print fidelity have been seen over multiple experiments [32, 42].

2.2.3 Hardware

As with the firmware, the design of the electrical hardware of these robots can reflect their traditional use as install-once industrial equipment. This is especially true when discussing robots from larger manufacturers as their product portfolios are more manufacturing than research-focused. Designed to do the same task repeatedly and with high repeatability, the components are hardened and robust rather than adaptable and computationally powerful.

One example of this processing bottleneck is the aforementioned issues with command streaming. ABB EGM documentation cites a 4 millisecond communication response time (250hz) [38]. This is however faster than the motion planner subroutine can parse commands (approximately 10hz) [42]. Users have had to adapt to this limitation by decreasing the fidelity of their RoMEX prints by limiting how quickly commands send [42]. The difference in computation power is also visible when comparing the responsiveness of the user interfaces of the ABB and KUKA robots. This highlights the differences between manufacturers' choices in processing power, even though these systems are near the same age in terms of industrial hardware (2017 and 2023, ABB and KUKA respectively).

System internals beyond computation also play major roles. More lightweight robots like those offered by uFactory integrate the robot controller into the arm base. This makes these robots, even those with similar payload ratings, more easily relocated or used with mobile bases. Separate controllers can be replaced or upgraded independently from the robot arms, although this process may require heavy machinery if relocation is necessary. The large physical size of these external controllers is driven by their significant internal empty space, many separate power and computer boards, large AC motor drivers, and an internal Ethernet network. Both KUKA and ABB also offer compact versions of their control cabinets, a feature that may come at an additional cost and less internal access space. The standard control cabinets from these large manufacturers are equipped with cooling fans that run at maximum capacity whenever the system is energized, regardless of load, resulting in a loud working environment. These cabinets are not typically sealed against dust, liquids, or insects; they are primarily designed to ensure human safety. This includes internal divisions between high and low voltages and safety lockouts.

This wide variety of sizes for electrical hardware is surprising given the similar payload of some of these robots. This is illustrated by the difference between the uFactory xArm 6 (10.5kg total weight, 5kg payload, circa 2023) and the ABB IRB 140 (98kg arm only weight, 6kg payload, beginning production in 1999) [43, 44]. The uFactory robot requires a 24 volt DC/10 amp power supply while the ABB IRC5 controller requires 3-phase 480 volt AC power [45, 46]. The controller for the lighter robot is integrated into the base of the robot, while the ABB controller weighs 150kg. Some of this discrepancy can be accounted for in that the ABB IRB 140 robot has approximately twice the average joint speed, about three times the manufacturer-reported repeatability, and a significantly heavier arm to move, all requiring more power. These factors themselves can be attributed to the level of robustness targeted by the two robots. The target market for the industrial ABB robot is heavy industry looking to automate one task for a large number of repetitions, while the uFactory arm is advertised for co-working with a human in a research environment.

2.2.4 Sales and Support

Another concern when using industrial robots, especially true with larger manufacturers, can be the sales and customer support model. These companies tend to approach, market, and support their products as typical for the industrial equipment sector, while smaller manufacturers are apt to use the consumer product model. For example, unless a customer is looking to purchase a significant number of robots, some large and medium manufacturers prefer to do both sales and basic technical support through a distributor. Across all sizes of manufacturers, however, higher tiers of technical support and customer training are often required to be purchased if desired, again exemplifying the à-la-carte model. Companies with fewer offerings often use frequently asked questions, wiki, and forum pages to assist and have bidirectional communication with users. In contrast, larger companies tend to treat these as a method for users to communicate amongst themselves, with documentation sometimes difficult to find at all.

As many robots represent sizeable capital expenditures, system designers may reserve using an articulated robot as something of a last resort. This is compounded by the added complexity of integrating one of these robots. Some companies ship devices with very little base functionality, preferring to upsell features to meet customer requirements. These add-ons may be referred to in documentation through a combination of ambiguous names, possibly trademarked marketing terms, or alphanumeric reference numbers. These companies also may require a technician to be sent out to perform these installations, maintenance, or troubleshooting, another service that is purchased. Larger manufacturers can offer 24-hour phone support, but for research applications, typical support staff on these lines may not be able to offer a solution. In contrast, smaller companies may only offer email or forum-based support.

3 Alternatives to Industrial Robots within RoMEX

Traditional industrial robots have benefits and drawbacks, but other options exist on the market today that may be a better fit for the unique application requirements of RoMEX. In addition to industrial robots, collaborative robots known as cobots are gaining in popularity and have a broad range of applications. Readers should note the intentional use of the words industrial robot vs cobot throughout this work, as there are several important distinctions and trends differentiating them. The following sections explore the differences between industrial robots and cobots both in terms of hardware and software integration.

3.1 Industrial Robot vs. Cobot

The majority of RoMEX systems use robot arms originally designed for tasks like automated welding and painting in the automotive industry. These industrial robots are built to repeat tasks behind protective barriers for long periods frequently in the range of decades. In contrast, collaborative robots are designed to prevent impact or injury while interacting in the same workspace as humans through extensive sensor integration. These include a combination of torque sensors at various joints to detect unexpected loads (indicating a collision), touch sensitivity on the robot limbs, elasticity in the actuator joints, and machine vision, which slows (but does not stop) the robot when something unexpected enters its working area.

Cobots come with their own unique set of benefits and challenges beyond being safety-focused. These robots offer smaller installation space requirements since no fence guarding is necessary and likely have a smaller upfront investment depending on the system. Barravecchia et al report that the differences in cost for a cobot versus an industrial robotic system vary by production environment, with the latter being more cost-effective for high-quantity production runs [47]. Their graphic of this trend is shown in Figure 3. However, unlike in assembly tasks, every additively manufactured layer may be different. When picking a robot as the basis of a RoMEX system, users should consider every aspect of the particular models and systems in question.

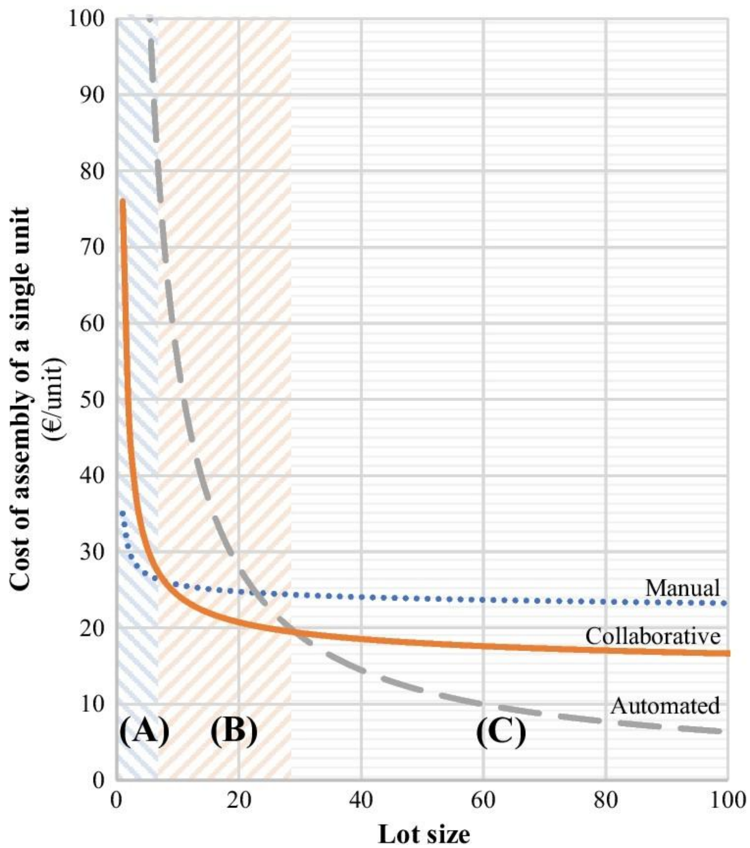

Figure 3: Cost per unit versus total production quantity [Lot size] for a generic assembly task using an industrial robot (Automated), a cobot (Collaborative), and by hand (Manual). Adapted from Barravecchia et al. [47]

3.2 State of the Industry

The following section outlines trends and observations of the robotics industry as seen in a recent industry-facing conference, as applied to RoMEX applications. An effort was made to collect robot catalog data from every manufacturer offering articulated robots at A3's Automate Conference in summer 2024. As a leading industry conference, billed as the "largest automation show in North America" [48], Automate represents a sizeable section of the robotics manufacturer space. Although this conference is international, the companies in attendance all had a sales presence in the United States and the companies in attendance were likely to be based or have a strong presence on the continent as well. An effort was made to include all robotics vendors in attendance, but the show data and information from these companies' websites are known to be skewed toward what is available on the US market at the time of publishing.

Comparing with the ABB IRB 140 and KUKA LBR iiwa 7 r800, articulated robots with 6 or 7 DoF with similar payload capacities were selected from manufacturers at the Automate Conference. When comparing multiple robots of the same payload capacity, the model with the longest reach was selected. This excluded special versions like those for cleanroom use and variations advertised as modifications of a base version (e.g., choosing the Yaskawa GP8 over the GP8L (long reach)). This also means that the data represented in Figure 4 focuses primarily on robot offerings with payloads around 7kg. The reader may notice a gap in payload ratings around 9-10kg. This is not due to a lack of offerings in that payload capacity, only that the offerings selected most closely matched the search criteria. Also note that, while the Igus ReBel was included as a budget option in this reach category, it was excluded from the following comparisons as it was an extreme outlier in all other categories.

Analyzing the body of data in Figure 4, several key trends emerge between cobots and industrial robots. The data represent a total of 22 manufacturers – four large, nine medium, and nine small (see section 2.1.2). However, there is no standard for reporting robot specifications, and not all manufacturers reported data for all the characteristics listed. Of note is the lack of non-proprietary software interfaces amongst the manufacturers with the largest number of robot offerings. These companies seem to be focused on offering solutions to challenges where the operation can be repeated and does not require complex software integration with outside devices necessary for RoMEX applications. This dataset intentionally included both an industrial and a cobot from each of these large vendors, keeping to the same requirements about payload criteria outlined in section 3.2. Cobots and smaller, newer companies tended to be more open to outside hardware and software applications including inputs and outputs as well as software interfaces. Of the 25 cobots investigated, 17 had out-of-the-box manufacturer support for non-proprietary software (68 percent), whereas only 4 of the observed 14 industrial robots offered this.

Another observation is that cobots are generally offered in larger payload increments within each series than industrial robots, regardless of manufacturer. This may be because cobots are still relatively new to the market and thus have fewer offerings or that they are applied to a wider range of task types. The cobots chosen here also tended to have lower average maximum joint speed (by about half) as compared to the industrial robots as seen in Figure 5. Lower joint speed limits maximum tool path/print speed and is likely related to several factors. This includes limiting speed

Manuf. Size	Brand		Payload (kg)	Reach (mm)	Add'l SW Interface	Cobot?							Joint Average	Repeat. (mm)	Ref**
L	ABB	IRB 140	6	810		no	200	200	260	360	360	450	305	0.03	1
L	ABB		7	1400		no							386	0.03	2
L	ABB	GoFa 5	5	1050		yes	125	125	140	200	200	200	165	0.02	3
L	ABB		10	1620		yes							161	0.02	4
L	Fanuc	LR Mate 200iD	7	717		no	450	380	520	550	545	1000	574	0.01	5
L	Fanuc		10	1636		no							393	0.03	6
L	Fanuc	CRX-5iA	5	994		yes								0.03	7
L	Fanuc		10	1249		yes								0.04	8
L	KUKA	KR 8 R1420 Arc HW	8	1421		no	220	210	270	430	430	630	365	0.04	9
L	KUKA		7	800		yes	98	98	100	130	140	180	124	0.1	10
L	Yaskawa	GP7	7	927		no	375	315	410	550	550	1000	533	0.01	11
L	Yaskawa		10	1379		yes	130	130	180	180	250	250	187	0.05	12
M	DENSO	VS-068	7	680	R,P,C,O	no	356	303	378	475	475	760	458	0.02	13,14
M	DENSO		6	908	R,P,C,O									0.03	15,16
M	Elite Robots	CS68	8	820	R	yes	150	150	150	230	230	230	190	0.03	17,18
M	Elite Robots		8	820	R		150	150	190				212	0.03	19,20
M	Epson	C8-A1401	8	1480	C	no								0.05	21,22
M	JAKA		5	954	R									0.02	23,24
M	JAKA	Zu 7	7	819	R	yes	180	180	180	180	180	180	180	0.02	25,26
M	JAKA		5	954	R									0.02	27,28
M	Kawasaki	RS007N-B	7	730		no	470	380	520	550	550	1000	578	0.02	29
M	Mitsubishi		7	920		no								0.02	30
M	Mitsubishi	RV-7FR	7	710		no	360	401	450	337	450	720	453	0.02	31
M	Neuromeka		7	1300	R,P,C	yes								0.1	32,33,34
M	Staubli	TX2-90XL	7	1450		no	330	350	410	540	475	760	478	0.04	35
M	Staubli		10	1000										0.03	36
M	Universal Robots	UR5e	5	850	R,P,C,O	yes	180	180	180	180	180	180	180		37,38
S	Doosan		5	900	R		180	180	180	360	360	360	270		39,40
S	Hansrobot	Elfin E-10L	8	1300	R,P,C,O	yes	100	100	150	150	180	180	143	0.02	41,42
S	Igus		2	660	R,P,C		45	45	45	45	45	45	45		43,44
S	Kassow Robots	KR810*	10	850	R	yes	225	225	225	225	225	225	225	0.1	45,46
S	Neura		5	800	R,P		170	170	180	180	200	200	183		47,48
S	Neura	LARA 8	8	1300	R,P	yes	140	140	200	200	220	220	187	0.02	49,50
S	Neura		10	1000	R,P		140	140	200	200	220	220	187		51,52
S	OMRON	Viper 650	5	653		no	328	300	375	375	375	600	392	0.02	53
S	OMRON		7	700			180	180	180	225	225	450	240		54
S	Standard Bots	R01	18	1300	R,P,C,O	yes	287	287	335	435	435	435	369	0.025	55,56
S	Tormach		6	975	R,P		150	112	150	204	225	360	200		57,58
S	uFactory	xArm 6 DoF	5	700	R,P,C	yes	180	180	180	180	180	180	180	0.1	59,60

*These models include a 7th joint: KUKA 180 deg/s and Kassow 225 deg/s maximum. **See Appendix A

Figure 4: Summary of robot offerings. While all brands supported their own proprietary programming language, many of the smaller companies also natively supported R=ROS, P=Python, C=C++, or O=Other options as well. Rated joint speed maximums for J1-6 are shown in deg/s.

for safely interacting with humans (an unnecessary concern for industrial robots). Interactivity also likely limits cobot arm speed, mass, and payload capacity as a heavy payload is difficult to stop quickly if a collision should occur. There is also the case to be made that very few applications with heavy loads (such as moving automotive chassis) require human-robot collaboration. Initialization of a RoMEX print does however often require close operator interaction even with large systems, so choosing a cobot over an industrial robot necessitates evaluation on a case-by-case basis.

The metric of average joint speed was chosen as an easy method of comparison as manufacturers' specifications for end effector speed varied from maximum (region within the working envelope was not specified) to typical with many not reporting a tool center point speed at all. Most companies did however report a maximum joint speed in degrees per second, so speeds for joints J1 through J6 were averaged (if the robot includes a 7th axis, this was omitted). It is acknowledged that this metric has low physical meaning given that wrist joints and base joints often differ in speed rating and robot limb length varies, but it provides a simple factor for comparison.

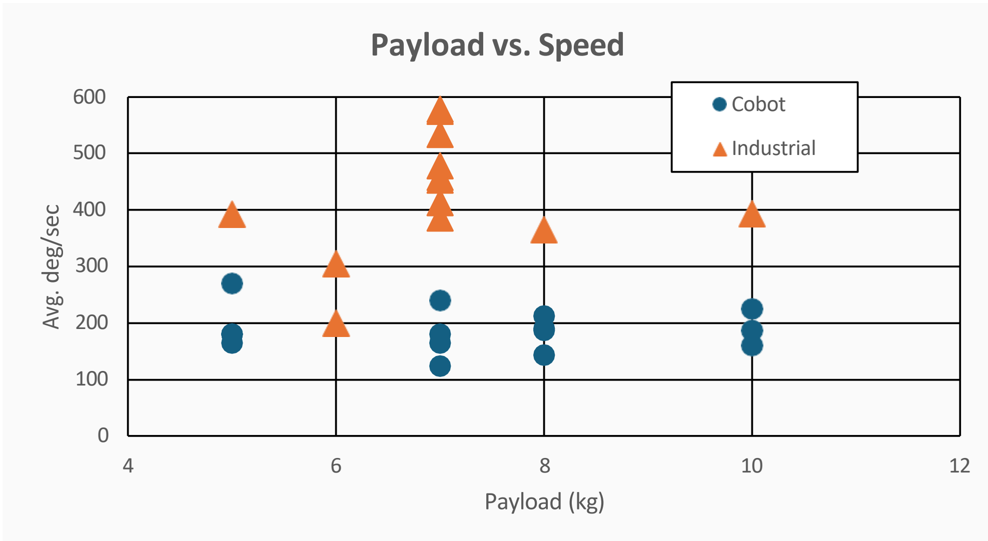

Figure 5: Payload vs. Average Joint Speed

While there was a clear difference between cobots and industrial robots in terms of speed rating, the two reported similar values when compared across payload and reach. Additionally, there was a bias for robots with larger payloads to also have longer reaches. This is shown by the slight upward slope of the data in Figure 6. This is somewhat confused by robot models that optionally come in long-reach versions which have been omitted here but were only available on the larger payload offerings. When selecting robots for inclusion in this study, within each payload rating the model with the longest reach was chosen if all other factors were the same amongst the options. While for polymer printing, payload capacity may be of little concern, when RoMEX printing in materials like concrete both reach and payload are important. It should also be noted that the maximum tip speed of a robot is not generally achievable at the rated capacity of the robot.

Collected data also indicates that cobots and industrial robots have comparable manufacturer-reported repeatability. Both types of articulated robots are "… highly repeatable, but not accurate" [49]. This is acceptable in human-adjusted programs that are repeated such as welding, but more problematic when performing one-off trajectories like those in additive manufacturing.

A detailed repeatability comparison between these two types of articulated robots is difficult to make. The wider spread of the cobot data may be indicative of different brands using different mechanisms (e.g. series elastic actuators versus strain wave gearing), even if using the same test. The settling time used in these tests for measuring the final location is also important. Regardless, there appears to be a slight upward trend in Figure 7 indicating that the larger payload robots (which may incidentally have longer reach per Figure 6) may have more variability in their positional accuracy (larger vertical spread in the plot). This may in part be due to the flexure of the arm limb segments themselves as their length increases. Consistent errors such as these may be eliminated in future work through calibration or predictive means.

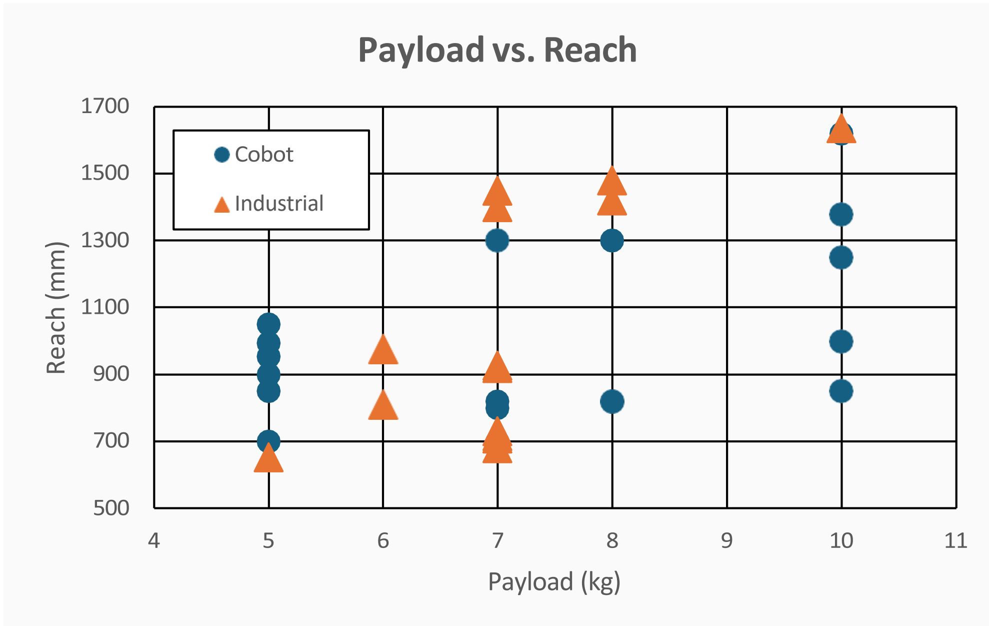

Figure 6: Payload vs. Reach

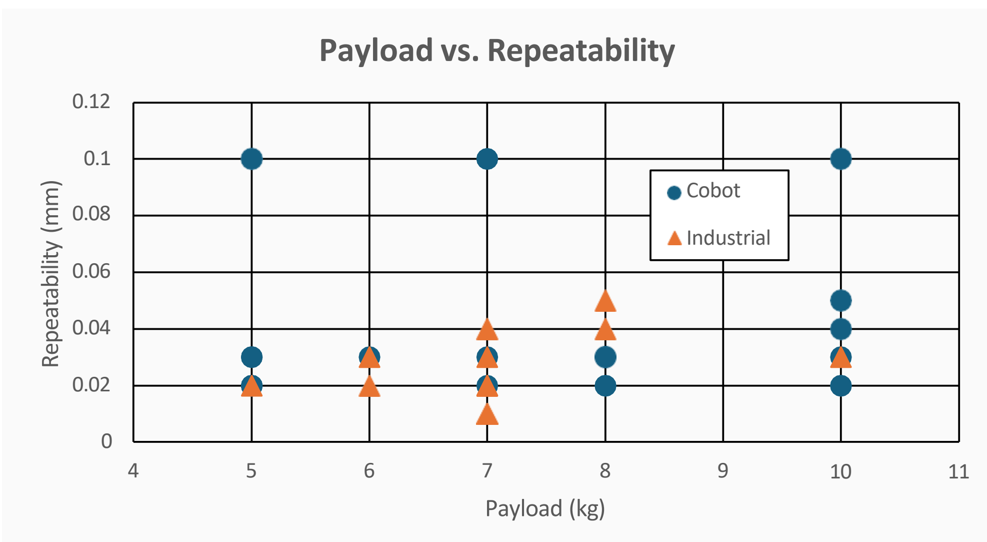

Figure 7: Payload vs Repeatability. Lower values indicate less variability between repetitions.

Figure 8 shows a summary of averaged joint speed, repeatability, and reach ratings across both types of articulated robots as tabulated in Figure 4. Category outliers were noted and one extreme outlier (Igus ReBel) was omitted from all categories for clarity. The hardware capabilities of these robots are surprisingly similar in many of the categories, even if the ease of software integration differs between size classes of manufacturers. The plot does however provide RoMEX-project-relevant insight into the range of abilities of both industrial and cobot articulated robots on the market today.

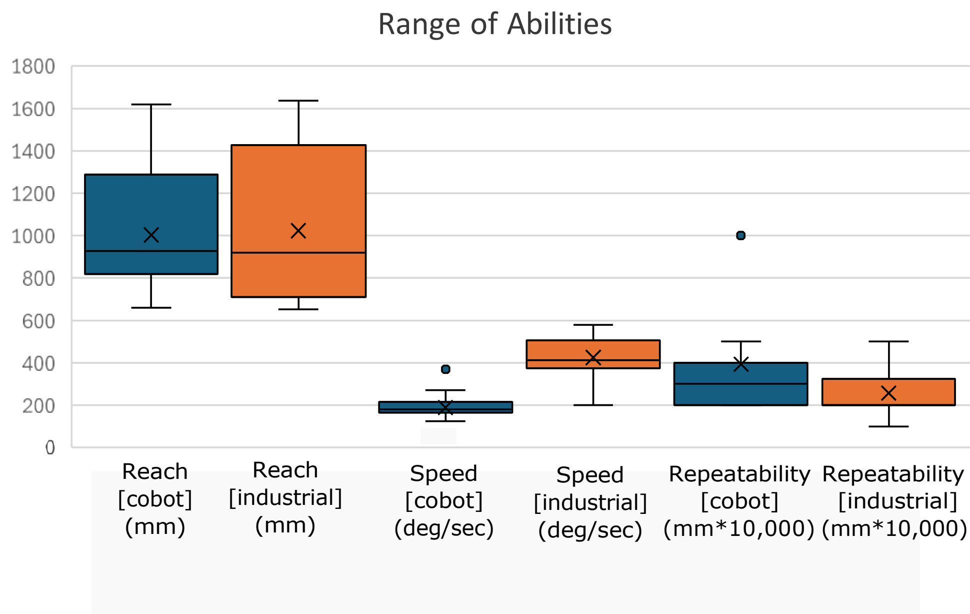

Figure 8: Overview of abilities for cobots and industrial robots based on data in Figure 4. The X symbol representing mean, and dots outliers.

4 Conclusions

While gantry material extrusion additive manufacturing systems can create objects layer by layer, unlocking the true potential of AM for engineering applications requires full nozzle orientation control. The most fitting actuator type to achieve this is an articulated arm robot. These mechanisms do not require additional rotation mechanisms to achieve full curved-layer printing and have the advantage of being able to bend to avoid obstacles. Established companies with more extensive catalogs tend to offer fewer methods of integrating their robots with outside systems than smaller companies. This communication with extruder, sensor, and other outside systems is required to implement a robotic AM system regardless of whether the designer chooses an industrial robot or a more human-compatible cobot. Few companies currently sell an articulated arm specifically designed to address the demands of RoMEX. However, there is increasing demand for turn-key robotic systems for use in use in printing applications.

Implementing a RoMEX system may present unexpected hurdles including establishing device communication, serious hardware and software limitations, and licensing challenges. The key hardware factors of reach, repeatability, payload, speed, and cost in addition to software integration and support are important to consider when designing a system from the ground up. While most articulated robot arms are physically capable, the larger manufacturers' offerings specialize in repeating the same task. The recent wave of lighter-weight industrial robots and cobots from medium and small manufacturers may cost less while achieving similar printing functionality. Importantly, these newer robots also tend to offer significantly easier integration with outside systems through standard software interfaces such as Python and ROS. Cobots generally offer this same software integration advantage while also offering the ability to work closer with humans safely. Overall, there exists many part strength, surface finish, and fidelity advancements to be made possible by robotic material extrusion, limited only by choosing the right articulated arm for the task.

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6 Appendix A: Robot Specification References for Figure 4

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