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Dexterous Printing and Fabrication of Multi-Functional Parts: Design for Science and Engineering Education

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Abstract

With the introduction of precision additive manufacturing techniques, the complexity of a particular fabricated part rivals that which is possible with conventional manufacturing alternatives. The drawback to this, however, is the time investment required to bring an object to its completion, which limits the practicality of an otherwise advantageous shift in manufacturing. To counteract this, an ambidextrous multipurpose hybrid machine (DEXTER), operating dual SCARA has been developed to reduce the time of single and multi-material builds. While the SCARA functionality brings forth new obstacles not inherent in conventional gantry setups, optimization studies were performed to minimize the irregularities in print performance. Ensuring a natural lateral movement in manufacturing practices between the traditional and dual arm approach. During prototyping, the current DEXTER model is being used to train the next generation in additive manufacturing, and to educate them on current manufacturing methods and devices. Doing so creates a generation with the skillset to join the workforce ready to take on the new revolution in manufacturing.

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1. Introduction

The objectives of this educational/research pursuit is twofold: (1) demonstrate the ability to teach the basics of electronics, and 3D printing using a novel printing prototype named for its dexterity and modularity (i.e. 'DEXTER'); (2) utilize a gamified prototype printer as a teaching module and distribute to neighboring K schools (i.e. Leon County School systems), to demonstrate advanced manufacturing concepts with 3D printing basics, in an easy to learn construct. The additive manufacturing (AM) prototype utilizes multiple Selective Compliance Assembly Robot Arms (SCARA) in a compact and modular environment in order to print materials simultaneously. Not only does robotic printing bring the opportunity to reduce the time required to complete a prototype, but current trends in "Hybrid Machines" demonstrate versatility in the application that could produce more complicated and structurally sound products in the aerospace, automotive and biomedical fields (to list a few)[1]. Although the principle of AM hasn't changed since its emergence (starting with a CAD model, separating the model into slices via STL, and constructing one layer at a time) the devices carrying out the process certainly have evolved. Multifunctional machines, such as the nScript line of 3D printers [2, 3], allow for the printing of conductive material within the layers of its thermoplastics, while the Matsuura LUMEX Av250 incorporates CNC milling alongside the laser sintering of metals[4]. The only drawback shared by each machine is the lack of a cohesive process when a change in material or process arises in more complicated builds. Essentially the time gap required takes away from one of the largest allures of AM, which is an increase in part complexity unachievable by conventional methods.

DEXTER aims to improve upon this, as each arm is fully customizable to better suit the needs of complex structures; effectively shortening the time spent printing each layer. The key to DEXTER lies within the use of multiple SCARA, which establishes a firm base for a multitude of different end effectors and manufacturing operations to be utilized. The first potential setup is allowing a single material to both arms for printing in nearly half the time. Another setup that could be used is ability to utilize multiple materials, which are printed simultaneously, to allow seamless integration of electrical circuits, dissolvable support material, or other structural materials. Lastly, the function of one arm could be replaced that of another manufacturing processes like CNC milling to further customize parts to shorten the distance to completing industrialized or reconfigurable manufacturing. In total, a faster turnaround for product completion means a considerable reduction in production cost as well as "Time-to-Market" and an increase in supply, which is an improvement for both consumer and manufacturer.

As a prototype, a modular ambidextrous printer (DEXTER) has been developed by participating undergraduate students in an NSF and AFRL sponsored Research Experience for Undergraduates (REU) associated with the Industrial & Manufacturing Engineering Department at the High Performance Materials Institute, along with graduate mentors to teach the basics of robotics and additive manufacturing. The final edition of this prototype will be delivered to schools as a kit as a classroom tool to teach robotics and manufacturing. This project is also being used to determine the machine vision and path planning of the actual printer to be built. Controllers have been added to control each arm manually, and a game has been programmed to represent AM working. Two people have to work together to create a pyramid, without blocking each other in or colliding. The game is won when the last block is placed on the top of the pyramid, and the time to completion is recorded in a beat the clock type game. Each person places blocks as fast as they can while building up the pyramid. This game was created to mimic additive manufacturing, and to teach the basics of AM by having players work together to build a part using blocks in a layer by layer manner. This type of competitive gamification teaches concepts such as path planning, robotic movements, and industrial controls. Kits to be constructed by the students are being compiled, along with a manual so that they are able to build their own DEXTER platform, thus teaching beginner electronics and engineering. The hopes are to inspire the next generation of engineers and scientists looking forward to entering the workforce in manufacturing associated with increasing materials technology in commercial industries, NASA, and Department of Defense.

2. Experimental Set-up

2.1. DEXTER fabrication

Two Arduino Mega 2560 are the selected microcontroller from which each SCARA arm operates. The Arduino library system and inherited C code structure provide a learning curve, as well as a significant technical support presence online that can quickly solve problems. Motor shields from Adafruit run two separate servo motors and single stepper without any jitters or feedback. As an open source platform, there also exists the ability to add on several other chips, such as Bluetooth or Ethernet connectivity in the future to make the system wireless, and the large Arduino community offered ample documentation to incorporate and implement.

Figure 1 shows the original design of the printer as well as a list of the materials that was used for the physical build. The arms were designed in house and printed using AXIOM Airwolf HDR printers. The nozzle contains electromagnets that are utilized for the pickup and dropping of magnetic blocks to achieve gameplay.

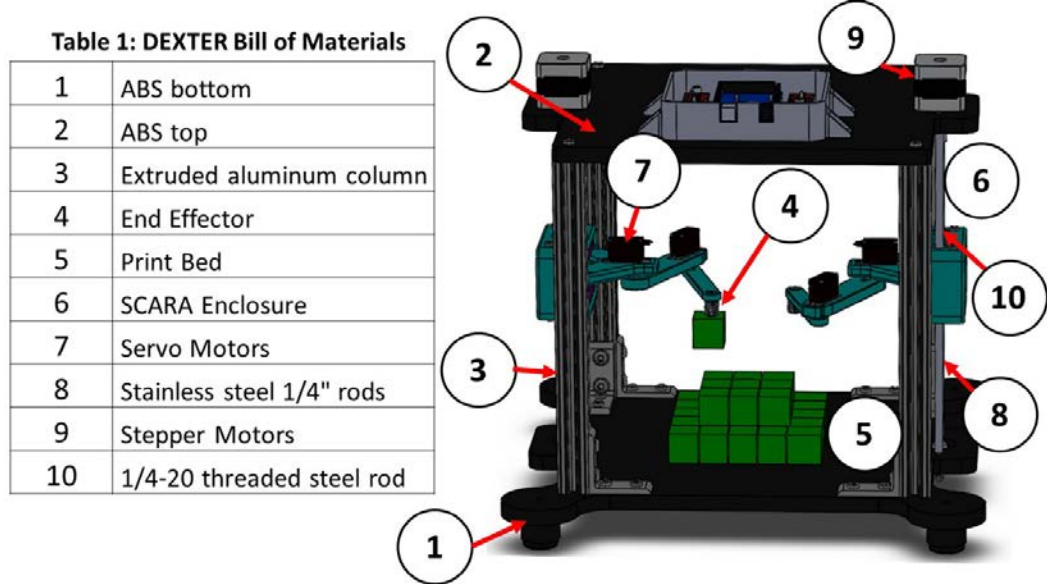


Fig. 1. Simple bill of materials and a breakdown of the DEXTER build (plus a visualization of the gamification by playing 'King of the Hill' type setup)

2.2. Firmware Development

MATLAB software was used for the calculation and conversions for a multitude of angular combinations of the arms, which would result in the possible locations the effector on the edge of the SCARA would be. The plotting function allowed the visualization of the "sweep" build envelopes of either arm. Various integration techniques were operated to determine the area of the print bed encompassed by the arms coverage and therefore optimized within an iterative case study of modifying the base angle setup. This ease of data visualization greatly benefitted the selection process for arrangement and reduction in existing dead space.

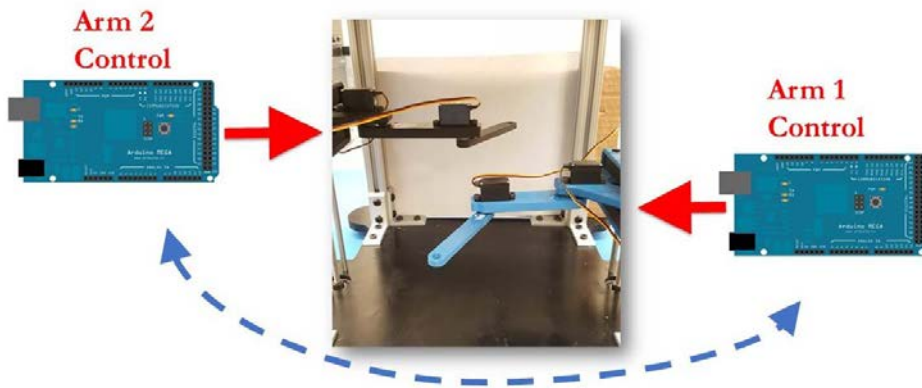


Fig. 2. SCARA control took place using two Arduino Mega2560, which communicated locations to each other serially

The coding of the platform took place within the Arduino IDE environment using C++, and two Arduino Mega 2560 as shown in Figure 2. This allowed for the utilization of the built-in functions for the motor control of both the z-axis stepper motors, as well as the servo motors used for the SCARA. Inverse kinematics were input to take in the x, y and z coordinates and convert to the angular movement that was needed for the arms to move.

2.3. 3D printing gamification

To turn the prototyping process for the main printer into an interactive and cooperative game, the following state diagram was used, as shown in Figure 3. The idea is to place blocks, one at a time, into a grid forming a pyramid structure. To begin, each player chooses a block the distance where to place the block in a strategic position, in the constrained grid. Certain rules must be established to control the flow of events and decisions concerning the complete build. Collision between players is not possible due to the collision control coded into the system. The same methodology prohibits the arms from traveling across already placed block or traversed space. This is similar to the game, Snake®, as, in additive manufacturing, a printer does not print over the same area that has been printed until the 2D layer is complete. Thus, with the game, the level cannot be completed until all the blocks have been placed. The game is won when a player places the block on the pyramid. As the game is cooperative in nature, the team of players can either win or lose the game depending on their degree of cooperation and process planning. There are cases where there is no winner, as one of the arms can block the other by laying a path that cuts off or inhibits the placement of blocks in certain portions of the grid. In this case, the system declares a 'draw' condition, and the game restarts. It is in the best interest of the game, for the players to communicate during the movement and operation of the robotic arm printer assembly, that the game can be won. This is parallel to how the arms in the printing DEXTER must also communicate to ensure that each arm is working collaboratively to print an object.

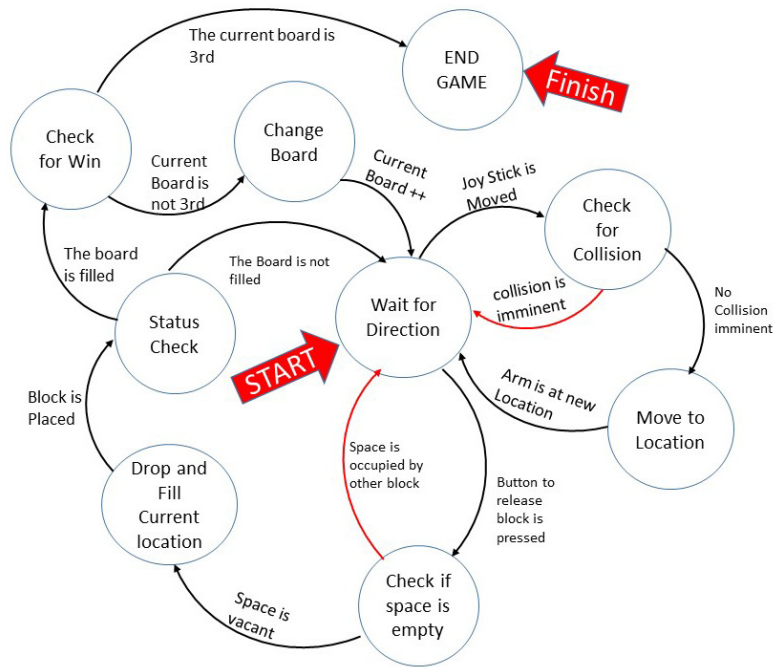


Fig. 3. State space diagram for gameplay of modular SCARA style 3D printer

The game is controlled by the individual using a joystick controller, where the joystick is used to determine which direction the player wants to ~~move~~ ~~move~~, and the buttons control the release and pick up of magnetic blocks via an electromagnet.

2.4. Path Planning and Collision Avoidance

Developing a printer dependent on the operation of multiple simultaneous SCARA begets unique benefits as well as troubleshooting in development. Collision avoidance ~~and~~ ~~and~~ planning of the end effectors must be taken into account, so neither SCARA can hinder the performance of the other or compromise the quality if the build.

To formulate an algorithm for DEXTER, insight from Qing Xue et al. and their collision free joint space for two cooperating planar robotic manipulators alongside the ~~time~~ ~~real~~ path planning of multiple degree of freedom manipulators by Samir Lahouar et al. was utilized initially [8]. Much like Qing Xue ~~et al.~~, each SCARA of Dexter was allocated to a separate microcontroller, to reduce computational complexity. Communication between the two allowed for Kinematic/Dynamic Coordination and minimized trajectory planning. The concept of a Boundary Follow method was explored by Lahouar et al., allowing for a system of decision making in the event of obstructing an arm from traveling to its intended ~~position~~ ~~position~~ as shown in Figure 4 [7]. In this image S is a pointwise robot that is seeking to reach the target q. The robot head towards the goal until a distance of d_i is achieved at which point it decides randomly to go left or right, keeping the same distance from the obstacle until there ceases to be an obstacle. At this point (C in the image) the robot continues on its path to the goal. The deflection process focused on more complicated systems which allowed for simplification in our application.

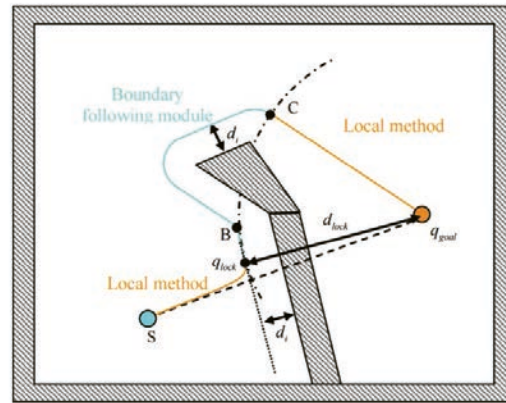


Fig. 4. Collision avoidance scheme used

Considering Dexter is a prototyping platform, the path planning takes into account fundamental aspects mentioned in the methods above. Each arm accounts for its own positioning and relates this information to the other, in a shared global mapping matrix. Since the inverse kinematics responsible for SCARA positioning return two results, the end position of each joint is tracked independently. An arm is labeled as “obstructed from its intended goal” when an obstacle is present in its directed path: in this state the arm is currently unable to finish its movement procedure (nor does it deflect randomly like that in Lahouar et al.’s manipulators)[7]. A boundary following procedure is ideal for future iterations of Dexter, and as of now, the only allowance given in collision detection is a predefined “buffer” that surrounds the arms (to avert unintended collisions due to the current lack of mechanical precision). It is important to note that much like the manipulators mentioned, there’s no precedence given to one arm over the other (nor is there any Master-Slave relation between hardware). The intended purpose of this platform is versatility, with each arm sharing an equal performance load, the system is truly flexible for a variety of use.

Eventually a more optimal form of dodge and avoid collision avoidance will be present in Dexter. This collision avoidance will take the proverbial “back seat” to pre-planned path planning for each print build, as open source software plugins such as Cura offer more reassurance and lower the margin for error than the current real-time decision making using firmware. To split and assign the independent paths of the arms before printing would minimize the chances of collision as well as interference with a build in progress.

3. Results and Data Analysis

3.1. Print bed Optimization

Unlike a typical cartesian printer system, SCARA can only operate within the area of their sweep, which does not encompass a square print bed as a whole. This is a drawback of a gantry system, as unusable “dead space” is something that leads to a smaller print bed. Also, the dual SCARA arm extruders can operate simultaneously only in a “True Build Area” which must be maximized to take full advantage of the ambidextrous printer setup. The upside of using SCARA is the small footprint of the robot itself, in this case two SCARA are housed within a total area of ~100 sq. in, as well as the ability to improve print speeds by 40% over that of cartesian systems. Though multiple print heads are available on existing printers, the ability to simultaneously use both at the same time is not available. In a cartesian system, only one extrusion head can be utilized at a time, due to offset considerations. In this setup, both arms can print simultaneously, allowing for dual manufacturing to take place.

In order to optimize the shared area and minimize the “dead space”, the primary angle of either arm must be changed to rearrange the sweeping area and the corresponding overlap. Through an iterative MATLAB Study, an angular offset of -48.75° was found optimal in increasing the total shared area to approximately 60% of the print

bed, and dead space reduced to about 6%. Figure 5 shows the mapping from both the non-optimized result, as well as the numerically optimized final orientation. In the original set-up the arms were set such that the main linkage was parallel to the bed at 0 degrees, and 180°. Now, when the main linkage is set to 0°, it is actually at a position that is 48.75° off the printable surface. This leads to a square area that is 5" by 5", and a print bed area that encompasses most of the 10" by 10" print bed.

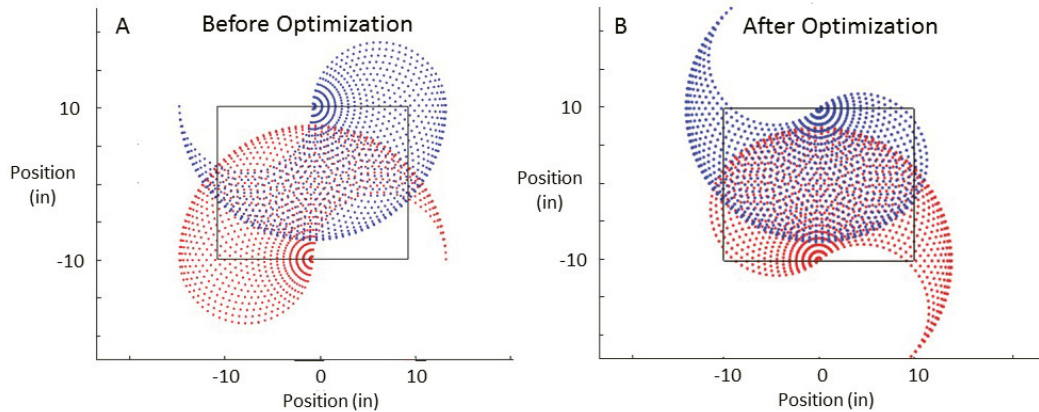


Fig. 5. Optimization results of dual SCARA print area

The teaching game is played within the 5" square shared area within the total build area, shown in Figure 6. The arms are physically able to reach behind them due to kinematics of the arm, but are constrained to the board by the frame surrounding the print area. While both arms can work in a square 5"x5" area, there is additional area in an ellipsoidal space that is considered shared as well, and is able to be utilized during printing.

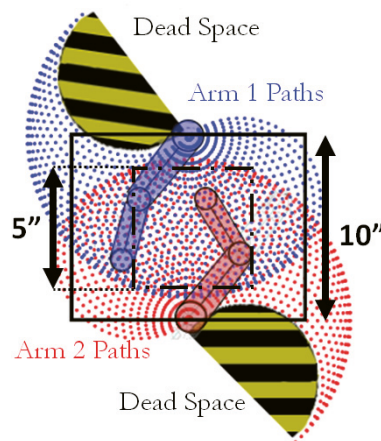


Fig. 6. Total print bed area, shared print bed area, and the overlay of the area that is able to be reached by each arm in the print

3.2. Collision Detection

Since both arms operate on the same plane, the propensity to collide within the shared build area is inevitable. To limit the occurrence of collisions, the algorithm implemented is the same as that used by MDDF (degree of freedom) manipulators seen in manufacturing/automotive industry. Since the manipulators work in a “dynamic environment” the algorithm leads to each machine categorizing the other as a moving obstacle, which it must dodge and avoid within operable space, as shown in Figure 6. Implementing this detect and avoid procedure will do away with collision altogether. Here, no single arms movement holds precedence over the other, and when obstructed from its goal position, simply follows a close boundary to avoid collision. In the case of DEXTER, since each arm possesses only two joints to move about, and are anchored at a single location opposite one another, it will be easier to implement path decision making to bias the arms deflection movements to the area where gridlock cannot occur, while the “goal” location is still achievable.

The algorithm applied has each arm constantly updating the placement of the other in a position matrix, this path planning allows the arms to track one another's movement and detect when a collision is imminent. The origin of the arm and the calculated location of its joints are used to vectorize the arm and establish multiple locations of occupancy where a collision can occur. With hardware limitations in the accuracy of movement and tracking of the arms, a buffer area is established as padding around each to avoid a collision in the event of the two arms crossing trajectories. This boundary following module is atribute shared in most manipulators in their collision prevention algorithm, to avoid the repercussions of the alternative.

3.3. 3D Printing Gamification Improvements

The 3D printing game shows promise in the ability to teach the adolescent novice about additive manufacturing, and distinctly robotic applications in advanced manufacturing system. The game functions in an ‘additive’ manner, that is, the placing of blocks works to simulate the fundamentals of additive manufacturing by adding material in a layer by layer fashion. Because each player has control of a single arm, they become the decision component of the manufacturing line, and thus they learn the ‘rules’ of additive processed manufacturing, such as, ‘3D spatial reasoning’, in terms of printing orientation, and that layers must be completed before the next sequential build layer is begun.

DEXTER itself comes with its own set of additional rules that are being tested via function of gamification. One of these rules is the aspect of collaborative player decisions. Cooperation is necessary for both the game and in versatile printing applications for a successful object build. As the layers are built players must talk to each other to avoid being either locked into a win scenario, as well as to try to complete a build as quickly as possible. In later iterations, a timing aspect of the game with a list of fastest times will be included to make the gamification more arcade-like. This makes the game approachable for younger students and education, in that the kit will be pre programmed as a game, and the game controllers can be used for younger students to use. In this way, young students can learn about cooperation as well as the current manufacturing techniques within a pervasive medium.

In 3D printing and manufacturing, the goal is to produce products in the fastest time possible to save on costs. In the same way, this game teaches that through cooperation and communication, the time to build a product can be reduced. Simultaneously, while researching the fastest times that players used to complete the build, these paths and approaches to dual printing can be used to optimize the dual build with two hot ends. For example, if it is found through playing the game that a certain approach to complete the pyramid yields the fastest times, then this same approach to printing can be taken into account when formulating the path planning algorithms. To make use of this, each run of the game should be saved to an offsite computer and algorithms to determine best printing effects can be monitored. These can be averaged into algorithms for the scale model.

4. Discussion

This project was started as a way to teach the fundamentals of additive manufacturing research to undergraduate REU students, while still creating a feasible object which could be passed over to regional schools as a kit that could teach robotics and engineering, and eventually becoming a buildable printing system. Figure 7 is a photo

taken from the entrepreneurship competition that was held at the end of the REU, where DEXTER was presented and explained to local business leaders.



Fig. 7. Undergraduate REU student pitches functional DEXTER system in local entrepreneurship competition

Going forward to the complete 3D printing machine, some aspects of DEXTER must be improved. The first issue found was in the communication system between the two Arduino boards, which was found to be too slow for immediate communication, thus a turn based algorithm was implemented to free up processing space. The game then proceeded as otherwise stated. It was determined that to turn DEXTER into a fully functional dual arm printer, that each printer must work of its own accord, driven by code as other current 3d printers. Thus the path planning and part division must occur within the slicing software itself, in order to have the processing power to control the two SCARA printers. In future models, the use of better path planning during printing and the addition of machine vision will help by moving the processing to the computer, and using the machine vision as a fail safe to detect impending collisions.

The current DEXTER project makes use of servo motors in the SCARA, which also limit the mobility of the arms, and make it difficult to turn into a fully functional printer due to these limitations. Servo motors work well during prototyping as they have the inherent capability to know their spatial locations. However, the resolution of these steps is too coarse for an excellent printing system. Thus stepper motors and a 3D printer board kit will be implemented to move towards an industrial type manufacturing machine.

5. Conclusion

In the completion of this project, the REU students gained valuable hands-on experience on fabricating and coding robotic systems, as well as MATLAB optimization, path planning, and obstacle avoidance. The students learned through this robotic assembly the intricacies of programming robotic systems, as well as the ability for time management to meet deadlines, and enhanced their coding skills previously learned in classes. The completion of the REU also gave them experience in additive manufacturing technologies while forcing them to view manufacturing from a separate angle in that they had to be able to teach it in a game. From this experience, a functional prototype was created, which will be improved upon before being distributed in the form of a 'hands on learning kit' to local schools as a trial run in their ability to help other students to become interested in STEM fields.

The DEXTER kit for high schools will contain previously manufactured parts as well as an instructional manual for build completion. The students would complete the remaining tasks of assembling by attaching arms with screws and completing the circuitry using a manual that would be provided with the kit. Once the kit is assembled, a fully functional Dexter game could be utilized by all ages and in that way teach the fundamentals of robotic collaboration, time management, and manufacturing as previously described. This gives the project a multi

objective educational impact, where the final project allows for the further teaching of the next generation manufacturing systems.

Future work on this project seeks to transition from megalay to a fully functional printer for composite materials using highgrade materials and 3D printer microcontrollers and firmware. The completed DEXTER project will leverage state-of-the-art technologies in advanced robotics and cybherical systems to enhance additive manufacturing of composite materials by allowing the simultaneous printing of multiple materials, as well as the ability of other manufacturing operations such as pick-place. This cybherical robotic system will also help reduce the use of supports during 3D printing and improve the precision during mating assembly between a pair of 3D printed components. Such a hybrid operation entails development of an advanced physical system to ensure accurate coordination and action control among robotic arms and the FDM process. Therefore, this project will provide the first demonstration in cybering composite material production through coordinated and networked manufacturing. The research will transform the composite structure manufacturing from molding to a high-performance CPS production system. The DEXTER project will leverage state-of-the-art technologies on advanced robotics and cybherical systems to enhance additive manufacturing of composite materials and manufacturing research capability in FAMU College of Engineering.

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