Linear Delta Arrays for Dexterous Distributed Manipulation

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Abstract—This paper presents a new type of distributed dexterous manipulators: delta arrays. Each delta array consists of a grid of linearly-actuated delta robots with compliant 3D-printed parallelogram links. These arrays can be used to perform planar transportation tasks, similar to smart conveyors. However, the delta arrays’ additional degrees of freedom also afford a wide range of out-of-plane manipulations, as well as prehensile manipulations between sets of deltas. A delta array thus affords a wide range of distributed manipulation strategies. In this paper, we present the design of the delta arrays, including the individual deltas, a modular array structure, and distributed communication and control. We also construct and evaluate an 8×8 array using the proposed design. Our evaluations show that the resulting 192 DoF robot is capable of performing various coordinated distributed manipulations of a variety of objects, including translation, alignment, and prehensile squeezing.

Index Terms—Parallel Robots, Compliant Joints and Mechanisms, Actuation and Joint Mechanisms

I. INTRODUCTION

The term dexterous manipulation often invokes the image of a five-fingered hand delicately holding an object, like a human hand. However, robots are not restricted to human morphology. Imagine instead a tabletop surface covered in fingers. Each finger can move its fingertip in a small 3D workspace above its fixed base and interact with parts of objects that enter its workspace. The fingers can work together to shift, tilt, block, and even pinch objects together. The large number of fingers provide additional redundancy, with larger objects being manipulated by tens of fingers at a time. The distributed nature of the fingers also means that multiple objects can be easily manipulated at the same time in different regions of the surface. This type of system would thus represent a distributed dexterous manipulation paradigm.

In this paper, we present delta arrays for distributed dexterous manipulation. Delta arrays consist of grids of small prismatic delta robots (3 degrees-of-freedom (DoF) each) that work together to manipulate objects. We propose a modular design for the delta arrays that consists of 2×2 units (12 DoF each) with each unit having a standalone mechanical and electronic design. Each unit has its own processor and controllers, allowing for distributed computation with a central computer providing high-level commands. We also present a real world implementation of an 8×8 array consisting of 16 units and providing 192 actuated degrees of freedom.

Each delta robot in the array is actuated by three linear actuators. These actuators are connected via parallel mechanisms to an end-effector platform, i.e., the fingertip. The platform and parallel linkages are 3D printed together out of soft material thermoplastic polyurethane (TPU) for easier assembly and to provide more compliant interactions. The linear-actuator design allows for the delta robots to be packed closely together, in a hexagonal grid, and their end-effectors to move outside of the footprint of the actuators. In this manner, the workspaces of neighbouring deltas can easily overlap, allowing for prehensile manipulations such as pinching between neighboring delta robots.

The delta array provides a basis for a wide range of different manipulation strategies. Similar to smart conveyors, delta arrays are capable of executing various planar transportation behaviours. Unlike smart conveyors, delta arrays need to use a finger gairting approach, with coordinated making and breaking of contacts across delta robots, to shift objects across the array’s workspace. This added complexity, however, means delta arrays can make better contact with objects that have non-planar surfaces. The additional flexi-
bility and non-planar motions of the deltas also allow for a number of other strategies. The variable height allows for rolling and tilting of objects on the array surface. Fingers can be raised to create fixture-like structures for aligning objects. The lateral motions allow the deltas to grasp and pinch objects of various sizes across the array. Although many of these strategies have been supported by other distributed or dexterous manipulation systems, to the best of our knowledge, this is the first system that supports all of these strategies and thus the possibility of combining strategies, as well as developing new ones.

Implementing and controlling an array of delta robots presents a number of challenges. The design needs to be modular for easy construction, extension, and repair. The individual delta robots need to be robust and safe, but also precise and capable of supporting a wide range of manipulation strategies. The communication needs to be fast and scalable to minimize delays between sending commands throughout the array network. In the remainder of this paper we will explain and discuss our design decisions in developing the delta arrays. In Section II we described related works. In Section III we present the design of the individual delta robots for close packing and overlapping workspaces. In Section IV we explain how the arrays are constructed using standalone 2 x 2 modules. Section VI describes primitive manipulation strategies for transporting objects. In Section VII we present experiments of the real delta array for distributed dexterous manipulation. The focus of this paper is on the design of the delta arrays and demonstrating its ability to execute a variety of distributed dexterous manipulation strategies. Developing more advanced and hybrid strategies is left to future work.

II. RELATED WORK

A. Delta robots

Delta robots, one of the widely used parallel mechanisms, were introduced by Clavel in 1990 and initially designed as a pick-and-place tool [1]. Conventional delta robots have a fixed base and a moving stage that are always parallel to each other. These platforms are connected by three kinematic chains with revolute and universal joints. These chains are each driven by single-DoF actuators that are positioned at the fixed base. The motion is transmitted from the base arm to the moving stage by three parallelograms, which are the key to the delta robot’s functionality [2]. In our recent work [3], we presented a gripper based on two prismatic delta manipulators using 3D-printed parallelogram links presented in [4]. Unlike traditional parallel jaw grippers, our robots have compliant end-effectors, which makes them modular and accessible. This 6-DoF system is able to perform dexterous manipulation tasks, such as aligning a pile of coins, picking up a card from a deck, plucking a grape off of a stem, and rolling dough.

B. Robot hand and finger design for dexterous manipulation

Current robot hands with fingers span a range of different designs and complexity. Basic two-fingered grippers often have a single DoF, while complex anthropomorphic hands will often have multiple DoF per finger. Current designs use serial mechanisms for the individual fingers, similar to human hands. However, the more dexterous designs either require relatively bulky motors to be placed in the fingers, where they significantly increase the inertia, or they are actuated by cable drives [5], which are subject to highly non-linear effects and temporal variations due to slack and friction along the cables.

C. Dynamic surfaces

Dynamic surfaces have potential to be used not only for object manipulation, but also as shape changing interfaces. Distributed manipulation systems have many types, such as vibrating plates [6], actively controlled arrays of air jets [7], planar micromechanical [8] actuator arrays, and actuated workbench using magnetic forces [9]. These dynamic surfaces with an actuator array are also widely used in interactive displays. A modular block system that utilizes motorized block system, TexelBlocks, is used for interactive applications such as context-aware surface adaptation, real-time tactile feedback, or real-time embodied platform game [10]. At small-scale, low-cost electromechanical actuator array is used to present a Braille device concept [11]. Larger scale dynamic displays using a single DoF blocks is proposed to be used to mediate interaction through shape changing capability and manipulating physical objects [12]. All of these examples focus on motion on a plane, rather than working on the motion in space, to introduced controlled motion along the third axis.

III. PRISOMATIC DELTA ROBOTS

A delta array consists of multiple delta robots arranged in a planar grid structure. In this section we explain the design of the individual delta robots. Each delta robot consists of three actuators connected by a parallel-bar linkage end-effector platform, as shown in Fig.2

A. Actuators

Delta robots are often designed with rotational actuators, such as servo motors, that provide torque to individual links [2], [13]. These designs provide rapid and precise movements at the end-effector, but at the cost of a wide robot base. The excessive width conflicts with the goal of creating a closely packed array of delta robots.

We utilize a novel delta robot architecture, based on linear actuators, which enables us to position each robot in close proximity of another. The three actuators are positioned in a triangular formation with their axes in parallel. The bases of the actuators are rigidly connected to each other.

We use linear actuators manufactured by Actuonix that possess a 50:1 gear ratio and operate at 12V and 1A, i.e. 12W peak power capacity. Each actuator has a 10cm stroke length. Internal potentiometers in the actuators provide analog feedback for position control. We implement a basic PID controller to servo the position of the linear actuators.
Rigid body delta manipulators cannot handle the stress of collisions against other delta robots. Thus, the low-cost compliant manipulator design in [3] has been selected for this project to minimize maintenance and take advantage of the inherent compliance of the 3D-printed delta links. To accomplish non-prehensile dexterous manipulation tasks effectively, the workspace of each robot intersects substantially with that of its neighbors allowing for the development of collaborative algorithms for robotic manipulation.

B. End Effector and Parallelogram Linkages

The three actuators are connected to each other by a parallel mechanism. The central end-effector platform is connected to the moving end of each of the actuators by a parallelogram link. This structure converts the prismatic motions of the three actuators into precise 3D x-y-z motions of the end-effector while keeping the platform at a near-parallel orientation to the base.

The platform and parallelogram links are 3D printed as a single part with living hinges. In this work, we design delta links with 0.375mm hinges and 4.5mm thick beams. For additional details of the design we refer the reader to our previous works [4]. We printed the structure from thermoplastic polyurethane (TPU). This material has a low Young’s modulus and results in a compliant structure. This compliance allows the robots to safely interact with objects and each other. By 3D printing the structure as a single part, we also significantly simplify the fabrication and repair processes for the deltas.

C. Delta Robot Workspace

A key benefit of the prismatic delta design is that the workspace of the delta’s end-effector extends beyond the triangular footprint of the three actuators. For our implementation, the horizontal distance between the centers of two actuators in a delta robot is 2cm, while the width of the workspace is approximately 6cm. To avoid excessive collisions between neighboring deltas, we restrict the horizontal workspace to a diameter of 3cm. The vertical workspace corresponds to the 10cm stroke length.

The delta robots are operated within a workspace that is far away from its singularities. Ambiguities in the inverse kinematics can therefore be easily resolved to determine a suitable joint trajectory for a given desired end-effector trajectory.

IV. MODULAR ARRAY STRUCTURE

The arrays are created by arranging sets of delta robots into a hexagonal array. Rather than constructing the array out of single deltas, we instead developed a modular 2 × 2 array unit for four deltas. Each unit can be operated in a standalone manner and provides a shared set of electronics and microcontrollers. To create an 8 × 8 array, we simply place 16 of the modules in a 4 × 4 macro grid, and a central computer then communicates to all of the modules to create coordinated manipulation strategies. The 2 × 2 modules thus provide a modular and extendable basis for easily constructing arrays of different sizes and replacing parts as needed. Our 8 × 8 configuration allows the manipulation of objects of a range of sizes and demonstrates the potential of such arrays in dexterous tasks.

A. 2 × 2 Delta Modules

Each 2 × 2 module employs a hexagonal structure as shown in the middle image of Fig. 2. The linear actuator bodies are held together using two 1/8in plexiglass plates that are precisely laser cut to dimension. The plates are supported by a total of 10 hexagonal aluminum stand-offs (45mm and 90mm), which creates a structure that secures the linear actuators at the top and the base of the actuator.
body. The stand-off configuration equally compresses the 12 linear actuators from both sides, thereby mitigating the chance of any loose fit or stray vibrations when the delta arrays are operated.

Each delta robot in the module is then secured individually through the housing at the base of the linear actuators using a 3D-printed connector constructed from Polylactic acid (PLA). The connectors are screwed to each of the three actuators in one delta and then attached to a 3D-printed enclosure made of PLA. This enclosure, or hardware box, houses the wiring and electronics needed to control the four deltas in that module. This enclosure also allows the module to be interfaced with a tabletop plate that supports all 16 delta robot modules. The resulting 2 × 2 delta modules offer the ideal balance between modularity and ease of maintenance.

The table top plate which supports the modules is constructed from a laser cut sheet of plexiglass. The plate allows the 2 × 2 prismatic deltas to seamlessly connect while providing wire routing holes and ventilation for each module. The plate is mounted onto pillars made of 80/20 aluminum extrusions which enables us to position the plate in any orientation. The silicone washers used to mount the plate to the 80/20 damps vibrations and prevents plexiglass from shattering under heavy stress of the delta arrays.

B. Electronics

To control the four deltas (12 actuators) in a module, we use Adafruit Feather M0 boards. These boards have a smaller form factor than the Arduino Megas used by our previous delta designs [3] and can thus be housed in the hardware enclosure box.

To control the prismatic deltas, we use the Adafruit DC Motor/Stepper FeatherWing and send PWM signals to control the velocity of the end-effector. On top of the FeatherWing, we attach an ADS1015 12-bit ADC which has a 4 channel programmable gain amplifier. Furthermore, since each FeatherWing has precisely four motor driver channels, we couple the position feedback from each of the four linear actuators with the ADC for precise position control. The ADC also provides the additional benefit of working as a low pass filter and eliminating the high frequency noise from electromagnetic interference generated in the circuit.

We use the I2C bus on the Feather M0 to send and receive commands to the FeatherWing and the ADC. To control 12 linear actuators, we stack up three FeatherWings and ADC pairs using a custom circuit that takes care of the I2C address adders as well as power delivery to the FeatherWings’ motor drivers. The FeatherWing I2C addresses are 0x60, 0x61, and 0x62, and those of the ADCs are 0x48, 0x49, and 0x4A respectively. A 12V 1A DC adapter is used to deliver the power through a barrel jack, which is then distributed across the FeatherWings using the shield circuit. The electronics choices enable us to create the entire circuit with a form factor of about 50mm × 60mm × 40mm, which can be easily placed under the footprint of the 4 delta robots above. The electronics also provides a distributed control framework, with all of the low-level control being performed within each module.

V. COMMUNICATION ACROSS THE ARRAY

The high-level coordination of the array is achieved by a central computer, which sends commands for the individual modules to follow.

We set up the communication framework between the computer and the modules in the array as a 2-hop system. The desired position control commands from Python are sent serially from the central computer over UART (using a CP2102 (RS232-to-TTL converter UART module) to all the Feather M0s. Since each Feather M0 has an internal pull-up resistor, we chain multiple devices on a single line and send commands to each of them without loss of information. However, the lack of an internal pull-up resistor in the CP2102 circuit design causes heavy signal attenuation when receiving feedback from the micro-controllers and limits the frequency of communication. We plan on incorporating wireless modules as a part of future work. A high-level flowchart of communication is shown in (Fig. E).

Communication between the central computer and the modules is performed using protocol buffers (protobuf). Protobufs are free open-source data structures that operate across multiple platforms and languages. Since we use both Python and Arduino (C/C++), protobuf offers a fixed schema with high compression rates in a binary format to satisfy the need for frequent, high-fidelity exchanges of commands among the devices. Protobufs also reduce the load on the serial communication network and increase fidelity of the commands being exchanged. The protobuf schema is given as follows:
Fig. 4: Communication flowchart for a $2 \times 2$ module. The control of three actuators of each robot in a four robot module is accomplished by three motor drivers. Colored arrows show the distributed control framework between drivers, actuators, and ADCs.

DeltaMessage{
    int32 id = 1;
    repeated float joint_pos = 2;
    bool request_done_state = 3;
    bool request_joint_pose = 4;
    bool reset = 5;
}

The key “id” identifies which $2 \times 2$ module the current joint positions are corresponding to. “joint_pos” contains a 12-dimensional vector describing the desired linear actuator positions. The remaining flags “request_done_state”, “request_joint_pose”, and “reset” are Boolean flags with the functions to request whether the desired positions are reached, indicate what the joint positions are, and decide whether to reset the delta array, respectively.

Commands are sent to the modules at 2.5 Hz. Future work will shift the computation of the inverse kinematics and parameterized desired trajectories to the microcontrollers.

VI. DISTRIBUTED MANIPULATION STRATEGIES

The completed $8 \times 8$ array can execute a variety of dexterous manipulation strategies distributed across its delta robots. These strategies include planar manipulations like translation, rotation, and converges, as well as out-of-plane and prehensile manipulations. To test the capabilities of the delta array, we have implemented a series of basic manipulation policies, or primitives. In this section, we describe these distributed manipulation primitives and how they coordinate the deltas in the array.

A. Two-beat Gait

The delta array policies are designed as two-beat finger-gaiting strategies that have the deltas repeatedly make and break contact with the objects being manipulated. Each linear delta robot follows a planar elliptical path. The planar trajectory moves in the vertical direction, to make and break contact, as well as along a horizontal vector as given by the high-level policy. The movements can be considered as going from $[-\vec{p}, z_{min}]$ to $[\vec{p}, z_{max}]$ as shown in Fig. 5. The two-beat gait means that half of the deltas in the array will be in an up configuration while the other half are in a down configuration, i.e., 180 degrees out of phase. We use a two-beat gait to maximize the number of deltas in contact with the object at a given time [14].

B. Dexterous Gripping Primitive

Apart from purely planar manipulation strategies, we also present a “grip-and-push” primitive that can be deployed to grasp objects within a line of delta robots and push the object forward or backward along the line. We use a two-beat finger gait, albeit on the $Z$-axis instead of the $X-Y$ plane and demonstrate the strategy on a form bell pepper as shown in (Fig. 6A).

C. Planar Translation Primitive

For planar translations, we first define the physical positions $(x, y)$ of the center of each delta robot in the $8 \times 8$ array. The policy for the delta arrays can be visualized by placing a point anywhere on the Cartesian plane and computing vectors for the delta robots individually. In Fig. 5 we show the vectors being computed for a point at the center of the delta arrays. A straightforward implementation of up, down, left, and right movements can be shown by placing a point along the $X$ and $Y$ axes at infinity as shown in (Fig. 5). These vectors are used in the aforementioned two-beat finger-gaiting pattern for planar translation of objects on the surface of the linear delta arrays (Fig. 6B).
Fig. 6: The rows of images demonstrate manipulations of different objects using the $8 \times 8$ delta array. The numbers beneath each row indicate the timestamp. (A) A toy bell pepper object that weighs $4g$ with a characteristic length of $60mm$ is transported from one edge of the array to the other using a translation primitive. (B) A box object is transported across the delta array using a translation primitive. (C) Same box object is rotated while the position on the array stayed same. (D) The toy bell pepper object is aligned against a wall of delta robots using the wall and translation primitives together.

D. Planar Rotation Primitive

For planar rotation, we break down circular rotation as a sequence of discrete translation vectors subsequently rotated by a certain angle, as shown in Fig. 6C. Rotation can be done about any center point by computing the distance vectors and then the dot product with the rotation matrix, thus giving us an array of circular vectors that rotate any object about the axis.

E. Wall Primitive

A unique feature of linear delta arrays is the ability to use a few delta robots and form a wall to restrict and concentrate movements along arbitrary wall shapes (Fig. 6D). Dexterous tasks like clamping or aligning an object along the wall and turning it around for inspection can be performed using simple yet effective policies.

VII. Experiments

This section describes the experimental evaluations performed using the delta array.

A. Results

We constructed an $8 \times 8$ delta array using the design described in Sections II and IV. We also implemented the distributed manipulation strategies explained in Section VI. The robot can then manipulate objects placed on top of the array. In our experiments, we show demonstrations of non-prehensile manipulation tasks on objects of various dimensions ranging from $60mm \times 40mm \times 20mm$ to $300mm \times 300mm \times 80mm$ and weights ranging from $4g$ to $1kg$.

Examples of different manipulations are shown in Fig. 6. Each picture represents a snapshot of the manipulation task being performed.

B. Discussion

The results show that the delta arrays can be used for a variety of manipulation types.

Planar translation and rotations perform better when applied to larger objects where more delta robots can make contact with objects at any time. Smaller objects can also be translated although they have a greater tendency to tumble.
during the trajectory and their overall trajectory is less smooth. In some cases smaller objects can also become stuck between delta robots in the array, but the compliance of the delta robots keeps the system safe in these situations.

The weight of objects plays an important role in the performance of the non-prehensile manipulations. We found that heavier objects tended to be manipulated more easily. Part of this may be due to the correlation in size. However, the heavier weight also increases the amount of frictional force between the delta robots and the object, and hence reduces slip. Adding high-friction finger tips to the deltas may provide better performance for lighter objects in the future.

The wall policy allows the delta array to successfully align objects against the side of sets of delta robots. In this manner the delta array can remove some of the uncertainty of the object’s position. The wall policy can also be seen as a hybrid policy that combines the use of the translational policy with using fingers as fixtures/obstacles. The delta array thus presents a suitable base for exploring a variety of mixed manipulation strategies in the future.

The primitives are currently being performed without any feedback from the object. The primitives must therefore exploit the redundancy of the array to generate robust manipulations. Incorporating an additional external sensor, such as a camera, would allow the robot to track the objects and apply more targeted manipulations.

VIII. CONCLUSION

We proposed delta arrays as a new type of dexterous manipulation robots. We presented the design of individual delta robots for close packing and overlapping workspaces. We also proposed a modular design and distributed control approach to support arrays of varying shapes and sizes. We constructed and tested an 8 x 8 array of delta robots. Our experiments showed that the delta arrays can be used to perform a variety of manipulation strategies. Our current manipulation primitives tend to be better suited for larger objects, where the redundancy of the array provides for robustness. To improve manipulation of smaller objects, we plan to incorporate visual feedback as our next step and apply more targeted manipulations.

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