Distributed Pneumatic MEMS for Fast Conveyance of Fragile Objects

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***Abstract*—In this paper we present a distributed and modular system to convey small and fragile objects. This is done by attaching similar modular blocks together to form a larger conveyance surface. Similar to other networked control systems, each block is composed of several sensors, actuators and communication infrastructure. Control of a levitating object should be done distributed and real-time. We emphasize on realistic simulations in multiple domains such as asynchronous control and communication. Simulations with two strategies on object motion show that we can meet all the real-time requirements for a successful conveyance.**

***Index Terms*—pneumatic MEMS, distributed MEMS, real-time system.**

I. Introduction

Moving very small and fragile objects has been studied through the capabilities of Micro-Electro-Mechanical System (MEMS) devices. In order to achieve it, two main categories of MEMS conveyors were introduced. The first category is grippers and ciliary actuators which have physical contact with the object. In [1], microgripping is presented as a way to grip and move objects. The second category is contactless, like pneumatic actuation and electromagnetic forces. Both also allow to move, sort and settle objects. In particular, [2], [3] study contactless micro-conveyors made of magnetic alloys and magnetic fields. In [4], [2], [3], [5], the design and fabrication of one conveyor are studied, whereas in [6] the application and control of ensemble of MEMS devices is studied.

Basically, our idea is to attach similar conveyors together and make a bigger conveyance surface. For that, using monolithic conveyors is not a good solution, because it needs to be rebuilt for each application. We therefore use modular conveyors. They are scalable, fault-tolerant and could be optimized to use a minimum number of conveyor modules. As a consequence, network delay, asynchronous control and non-precise sensing will be the tradeoff of our system. Fig. 1 shows the basic idea of how modular blocks can be used in order to move small object over them [6]. In order to study distributed algorithms, communication infrastructure and control of our system, we design a simulator. This simulator is event-driven and can simulate group of modules, communication among them and the physics laws applied to move objects with micro-second precision.

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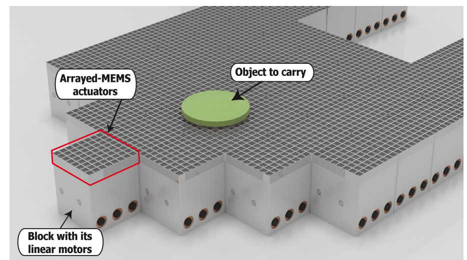


Fig. 1: Basic Concept of Modular Conveyor.

The remainder of this paper is organized as follows. In Section II, we briefly go over the previous works. In Section III, we present our design and architecture of the blocks, the aerodynamics of the system and communication infrastructure. In Section IV and V, we briefly present the distributed object recognition and strategies for object motion respectively. In Section VI, we show our simulation results, and finally Section VII concludes the paper.

II. Related Works

Previous works regarding this research is in two domains. First, MEMS-based and contactless systems for applying forces to move an object. Second, modular robotic systems which use modular robots attached together to fulfill a goal.

In [3] an Intelligent Motion Surface has been introduced as a fast manipulation surface. Authors used arrays of micro-robots programmed as an ensemble of robots for manipulating the objects. Using air force for conveying object as a contactless moving paradigm has been addressed for fragile objects or medicinal products.

For moving small objects, different paradigms have been introduced and implemented. In [7], a robotic air-jet was presented for moving objects with 2-DOF (Degree of Freedom). In [8], a high-speed conveyor was introduced and tested for moving fragile objects. Another type of pneumatic micro-conveyor was presented in [9] for moving micro objects. Another surface manipulator used for moving and sorting objects, SmartSurface, has been widely studied through modeling of air jets, open-loop vs closed-loop, distributed algorithms etc. Fig. 2 shows the SmartSurface which we use it hardware for our tests.

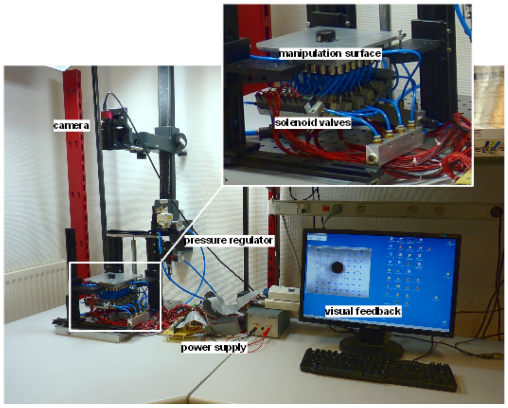


Fig. 2: Hardware set-up of SmartSurface.

In all previous works on pneumatic systems, the whole system is based on one solid part which makes the object levitate using air force.

Modular robots has been studied in a variety of projects like Kilobots [10], M-TRAN [11], Superbot [12], Molecube [13] and roombots [14]. Superbot, Molecube and roombot are self-reconfigurable robots similar to our research except that most of those researches are 3-D whereas we use 2-D. In [6] a self-reconfigurable robot with array-based MEMS actuators on top was introduced. This concept which is the foundation of our implemented system used Electro-Permanent Magnets to join and disjoin the modules.

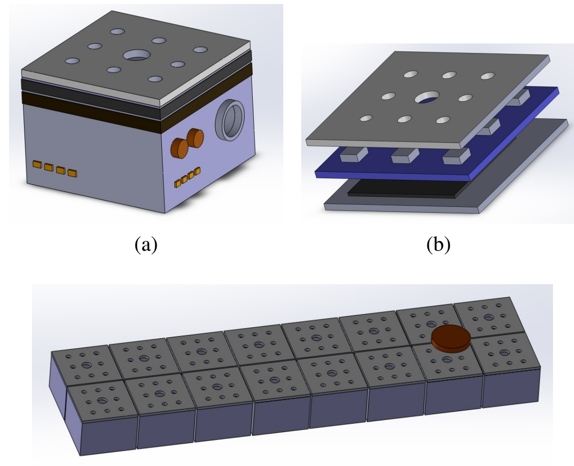
III. Architecture of Distributed Pneumatic Blocks

In this section we will introduce the distributed pneumatic system for moving objects. This system uses air forces to lift an object on an air-cushion, afterwards to move it.

In order to move an object over a distributed pneumatic MEMS, the blocks consist of three layers, as shown in Fig. 3. The top layer is formed by the pneumatic MEMS and the sensors, whose role is to blow the air to the above area. The air flow is used for accomplishing two tasks. First, to levitate an object over the whole surface; second, to make a large air flow in front of the object to pull it. Besides, in the first layer we have installed some proximity (on/off) sensors to detect the presence of the object over the block. The middle layer is the electric layer, the printed circuit board (PCB), used for controlling the valves and sensors. Its design is not relevant to the current topic. The bottom layer is the controller and the communication infrastructure. In order to make a big conveyance surface we should stick the blocks together. Fig. 3 shows that blocks could stick together and make a surface to convey the object.

A. Aerodynamic Effect of Airjets over the Object

In this section we briefly introduce the impact of air flows over the object. In [15], the basics of fluid mechanics have been introduced. In [16], it has been suggested that any vertical airjet could be considered as a sink which attracts the air



(a) (b)

(c)

Fig. 3: Schematic view of Smart Blocks, (a) a block, (b) top layers of a block consisting of sensors and an actuator, electronic and microcontroller, (c) group of attached blocks making a bigger conveyance surface and an object over it.

through itself. Equation (1) shows that the velocity vector of the air $\vec{U}_i$ has direct relation with the strength of i^{th} sink which is Λ_i and inverse relationship with distance of the sink which is r_i. $\vec{e}_{r,i}$ is the unit direction vector from sink to the center of the object.

$$\vec{U}_i = -\sum_{i=1}^{k} \frac{\Lambda_i}{2\pi r_i} \vec{e}_{r,i} \tag{1}$$

From [16] the given forces in each dimension are as follows:

$$\begin{cases} F_{air,x} = \sum_{i=1}^{N} -\frac{b}{2\pi}[f_1 \cos(\phi+\theta) + f_2 \sin(\phi-\theta)]\Lambda_i \\ F_{air,y} = \sum_{i=1}^{N} -\frac{b}{2\pi}[f_1 \sin(\phi+\theta) + f_2 \cos(\phi-\theta)]\Lambda_i \end{cases} \tag{2}$$

The details of aerodynamics are beyond the scope of the current paper, but according to (2) the applied forces at any time to the object is the superposition of the forces applied by all sinks.

In our simulator and models we use these aerodynamic equations to implement the effect of airjets over the object.

B. Communication and Constraints

Before we present our distributed system, we will state some rules and constraints among the whole system. According to (1) the applied force to an object has a reverse relation with the distance of the object to the position of the open valve. So, we define a parameter called effective radius which means the maximum distance from the object as which the open valve could have a noticeable effect on it. In the current paper, the effective radius is considered to be ten centimeters. As a result, we consider in our basic design that any given intelligent block just has information about the position and status of the blocks within the effective radius. The status of a block consists of

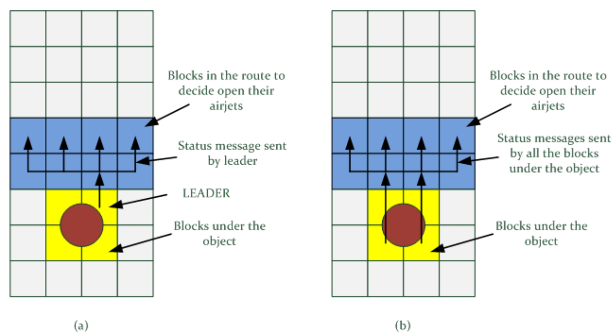


Fig. 4: (a) Leader-based strategy, (b) Information forwarding strategy.

many information, such as opened or closed valves and on/off sensor statuses.

In order to exchange status of the blocks and objects in the whole system, we propose a Serial Peripheral Interface (SPI) for peer-to-peer communication within the neighboring blocks. Each block sends and receives messages from the four neighbouring blocks.

IV. Object Recognition

In [17], object recognition in the context of distributed movement of the object has been introduced and experimented. We implement a similar strategy which has differences comparing with that system. The first difference is that the blocks in our experiment are asynchronous, which means different blocks could be in different states. Secondly, the communication infrastructure for message passing is distributed, non-deterministic and has real delays.

When the object is placed over the blocks the binary representation of the object is extracted by proximity sensors. In real pneumatic object levitation, the object does not stand still over the surface. Actually the object is vibrating randomly because of the air turbulence, effect of the airjets over the object and imperfect flat surface underneath the object. So, while the blocks are trying to discover the shape of the object with message passing, there is a probability for the object to move, consequently change the shape of the object.

Object recognition and reconstruction should be done when the object moves over the surface. All the blocks in the trajectory path should know the position and shape of the object. We have approached this problem in two different ways. First, we have implemented a leader-based algorithm, where the leader is the block considered as the right-most and top-most block under the object considered as the responsible for the shape reconfiguration. The matter which let us implement such technique is because the total message passing for object recognition will be less. Second approach, called information forwarding, is that each block sends the status of its sensors to the next blocks in the route, then each block construct the shape of object and decides whether to open its valve or not. Fig. 4 shows the operation of two different strategies.

V. Object Motion

In this section we present the movement of object over the surface built by modular blocks.

A. Verification of the Object Motion

Before discussing our distributed control algorithm, first we will explain how we have verified our model and simulator by using real data captured from SmartSurface. In this procedure we have conducted experiments which move the object over the surface. We capture the position of the object, status of each airjet from the real system. After gathering the data from the real system we apply the same scenario to our system simulator. In addition, we have added random noises caused by air flows, parasitic noise of levitation airjets that make the formation of the object movement. Finally, the model and simulator came to work the same as the real system with the maximum error of 2 millimeters on object position.

B. Object Movement Strategy

In this part, we propose two different strategies to apply forces to the object. These strategies are based on the object recognition techniques presented in the previous section. In the first strategy (leader-based strategy), the leader reconstructs the shape by exchanging messages with the other blocks under the object, then sends the position and status to next blocks in the path. Second strategy is that the blocks under the object send object information to all the blocks in the path, so each block according to its pre-programmed control law will make a decision for opening the valve or not. Fig. 4.a. and Fig. 4.b. show the command message dispatch from the leader-based and information forwarding strategies respectively.

C. Scheduling Policy

Different messages for different tasks such as leader election, status exchange etc. might appear in the middle of other tasks execution such as control algorithm. If a task started (any message can be implied as a new task), it would be queued and processed according to its deadline. Some tasks, such as control to decide for opening or closing a valve and object recognition, are considered as hard real-time, so their deadline should not be missed. The missing of such deadline may lead the object to either running over an open airjet or getting out of the trajectory. In either cases the object may hit a solid place and damaged.

In our implementation we have made the following assumptions. All the tasks are nonpreemptive and all the messages are categorized in different levels of priority. The categorization of the messages are performed off-line by the designer and according to the design goals. We used dynamic priority scheduling for incoming tasks; therefore, we decided to use the Earliest Deadline First (EDF) as scheduler in our implementation [18].

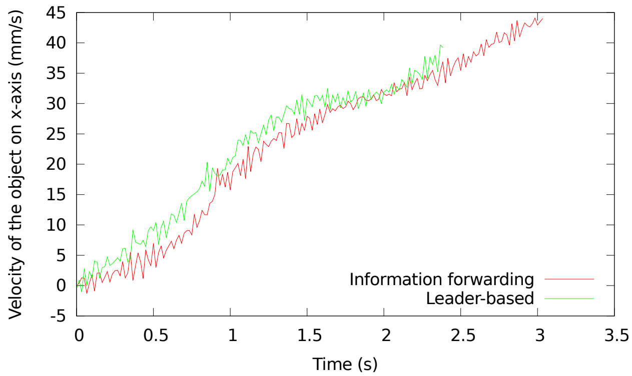


Fig. 5: Velocity of the object for the two strategies with one row of open airjets.

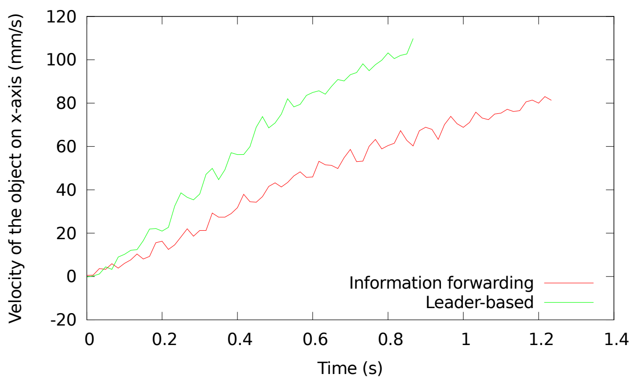


Fig. 6: Velocity of the object for the two strategies with three rows of open airjets.

VI. Simulation Results

In order to express the results we use 12×12 blocks that shape a conveyance surface. The goal is to move an object from left to right. In each experiment, the velocity of the same object for the two strategies (leader-based and information forwarding) is shown in one axis. Fig. 5 and 6 show the velocity when only one row or three rows of airjets in front of the object are opened, respectively. Fig. 5 shows similarity between the two strategies. On the other hand, Fig. 6 shows that the leader-based strategy performs better. This is mainly caused by the high traffic imposed by many messages of the second strategy to the network. As a result, the delays in message reception accumulate and cause the next blocks in the trajectory to open their valves later than in the leader-based strategy.

VII. Conclusion

In this paper we presented a distributed real-time system for conveyance of small and fragile objects. We have implemented a precise model of airflows and its physical impact over levitating objects.

We have successfully designed a surface where objects levitate and move. We implemented the reconstruction of an object using proximity sensors over blocks by a completely distributed algorithm. We also proposed two strategies for object reconstruction and control; faster conveyance is obtained when using a leader block which gathers all the information then dispatches it to next blocks in the trajectory.

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