研　究　速　報

Autonomous Decentralized Systems Based on Distributed Controlled MEMS Actuator for Micro Conveyance Application

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1. Introduction

Many examples of *distributed Autonomous Decentralized Systems (ADS)* can be found in nature. Animal as insect societies provide us a vast number of self-organization patterns as observed in the behavior of bee and ant societies. These phenomena's can be also met in the human society. For instance, we can see emergent mechanisms in economic markets or politics, which are ruled by the local behavior of their individual participants[1]. Another fascinating example of distributed ADS application is the self-organization of the human body itself, as the neural network organization of human brain.

To analyze the concept of distributed ADS, we have to consider that a global system can be composed by a very large number of units, each unit being able to:

- decide its actions by itself in communication with its local neighbors (autonomous systems),
- have its own integrated intelligent, that it does not require a central control unit (decentralized systems),
- well divided up so as to allow good functionality of the global system (distributed systems).

Distributed ADS in MEMS technology

Using Micro Electro Mechanical Systems (MEMS) technology, it is possible to fabricate micro actuators with dimensions of 5 to 100 μm, and to integrate them with sensors and circuitry. Besides the miniaturization, MEMS technology allows batch fabrication of identical devices on a planar substrate, which reduces assembly to a minimum. This technology is perfect for distributed ADS, that can be called in that case *distributed Autonomous Decentralized MEMS (ADM)*, and recent studies have been investigating this potential.

Micro-flaps all over an aircraft wing would allow roll maneuvers, and if combined with turbulence sensors could help to reduce drag[2]. Other research is developing an artificial retina, which combines CCD elements and preprocessing operations like edge detection on-chip[3]. Object transfer by belt conveyor and robot manipulator is also usually applied with distributed ADM.

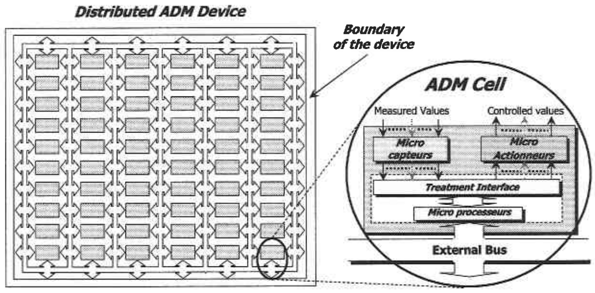

Fig. 1: Structure of distributed ADM device

Figure 1 present a general structure of distributed ADM, which is based on a multiplicity of cells commutating between each others. In technology, each cell is a micromachining device composed by a micro actuator, a micro sensor and a micro processor with its treatment interface to treat measured and controlled values, as shows by the ADM cell schematic of the figure 1. Communication between all cells is made possible by a simple external bus. Finally, the architecture of the ADM cells can be developed in MEMS technology associating microelectronic component. Each distributed ADM device is defined with its boundaries in anticipation of future connections.

Micro manipulation based on distributed ADM

As referred previously, distributed ADM, just as distributed ADS besides, can be exploited in field of micro or macro manipulation scale. In robotics, we use general terms of "distributed manipulation systems" which can induce motion on objects through the application of force at many points of contact[4,5]. This approach offers new possibilities with many advantages as well as in macro than in micro scale, that can be given by:

- many small inexpensive mechanisms can move and transport large heavy objects (in regard from scale),

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Fig. 2: Conceptual picture of distributed manipulation

- parallelize can enhance flexibility of manipulation,
- it can save space,
- if one component breaks, the other components can compensate for the failure.

The conceptual picture of the figure 2 shows a macro manipulation example of one person conveyed over a crowd by masses of people. Each people of the crowd can be compared to an autonomous decentralized system well distributed to carry out the manipulation.

Distributed manipulation has drawn attention in several recent studies, particularly in the micro scale area. They do not follow the principle of providing one micro actuator for one degree of freedom of the manipulated micro tool or micro object.

However, to design micro conveyance systems, we have to take into account functions such as recognition, conveyance, and positioning of a micro object. There are key devices to handle small objects in the microscopic world. To realize such intelligent functions without external control, we have proposed to perform cooperative operation of distributed ADM in the same device. The Smart MEMS design approach, which will be presented hereafter, is proposed to achieve such complex technical development.

This research in field of distributed ADM fabrication was the subject of many studies those ten last years within *Pr. Fujita laboratory* belonging both *CIRMM/IIS* and *LIMMS/CNRS-IIS* of *The University of Tokyo*[6]. We present here recent researches in this field, introducing principles and conception of a pneumatic micro conveyance based on distributed ADM actuator.

2. Distributed MEMS actuator concept for pneumatic micro conveyance

Several structures of distributed MEMS actuators have been developed in the field recently. We can list main significant researches such as *Ataka et. al* and *Suh et. al*, presenting micro ciliar motion systems[7,8], *Nakazawa* who showed a magnetically driven micro conveyor[9], *Boringer et. al* using a micro vibration mechanism[10], and finally, *Pister et. al, Konishi et. al*, and *Guenat et. al* who proposed a pneumatic air flow for micro actuators[11-13].

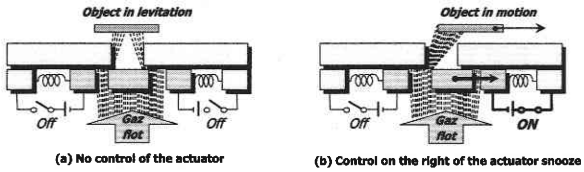

Fig. 3: Principle of the air-flow micro actuator.

These last developments with a pneumatic approach mainly keep us attention. Indeed, pneumatic micro conveyance systems have a lot of advantages such as: 1) no friction problem, 2) no particle generation, 3) generation of force large enough to convey micro objects.

From 1999, within *LIMMS/CNRS-IIS* and *Pr. Fujita laboratory*, the concept of micro conveyance system based on distributed airflow micro actuators was studied, as presented hereafter.

PRINCIPLES OF THE AIR-FLOW MICRO-ACTUATORS

Cooperation of many MEMS actuators makes it possible to convey a micro object relatively larger than each micro actuator component. The proposed micro conveyance system is composed of the array of MEMS actuators, which can regulate not only the on/off motion but also the direction of air-flow.

Figure 3 illustrates the cross-sectional structure of the MEMS actuator and principle of controlling air-flow. The MEMS actuator is composed of two silicon substrates. The top substrate has a through-hole for air-flow. The bottom substrate has a movable part with suspension beams electrodes that works as a normally-close valve. When the movable part is driven toward the left, the right-hand side hole of the movable part opens to eject the air to the left (Fig. 3a → Fig. 3b).

Moreover, one of the critical issues of the air-flow conveyance system is durability of micro structures. By the bulk micromachining technique, we have developed a robust MEMS actuator-array whose fragile moving parts are hidden under the protective bulk silicon structures.

REALISATION OF A ONE-DIMENSIONAL PNEUMATIQUE MICRO CONVEYANCE SYSTEM

A first one-dimensional prototype of the pneumatic micro conveyance system by bulk micromachining technology was achieved in 2000 by *Arai et. al*[14].

Its dimension is 13 mm × 13 mm and it has an array of 169 micro actuators. A direct bonding fabrication method of the airflow micro actuators was used that has significant role to make dual substrates structure. Almost all the micro actuators have been successfully released, because recess on the back surface of movable pattern before wafer bonding process makes it possible to use dry etching process instead of wet sacrificial layer etching process at the releasing procedure[15].

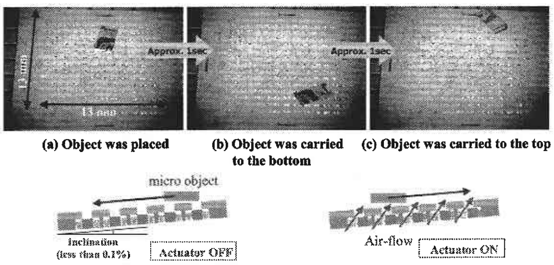

Fig. 4: Micro conveyance experiment of 1 D motion

Figure 4 shows experimental results. We observed one-way motion of the placed object due to the slight inclination of the micro conveyor surface (less than 0.1%; the upper-side of the micro conveyor was higher than the lower-side in Fig. 4). We used air-flow of up-hill direction to convey a micro object.

A silicon chip of 2.1mm × 4.1mm (~ 4mg weight) was placed on the upper-side of the conveyer (Fig. 4a). By applying a 17 kPa air pressure (nitrogen gas) without using the nozzle micro actuators, the micro object was found to be lifted up and moved to the lower-side by 8mm in approximately 1s (Fig. 4a → Fig. 4b). Subsequently, all nozzle actuators were operated by applying 150 V to make upper-direction again (Fig.4b → Fig. 4c).

3. 2D micro conveyance Design by controlled distributed MEMS

From 2001, previous researches have been continuing by *Y. Fukuta*, within *Pr. Fujita Laboratory*. *Y. Fukuta* carried out a two-dimensional micro conveyance prototype, by first optimizing the fabrication process of the distributed MEMS actuators and afterward developing an appropriate technique to control MEMS-arrays[16].

FABRICATION PROCESS OF AN ARRAY OF AIR-FLOW MEMS ACTUATOR

Micro actuators fabrication process

The way we proceeded to fabricate a simple micro actuator is the way we followed for MEMS-arrays.

Thus, an SOI wafer which has 100 μm thick SOI layer, 2 μm thick BOX layer and 100 μm thick silicon base substrate was used. Figure 5 presents fabrication process steps of the two-dimensional micro conveyance system. Firstly, the air channels were made at the silicon base substrate by the Deep RIE (Reactive Ion Etching) process with photo-resist mask (Fig. 5a).

Secondly the SOI layer was patterned into the micro actuators by the Deep RIE process with photo-resist mask (Fig. 5b). Then, the structure was oxidized to make silicon oxide layer on the surface of structure (Fig. 5c). Subsequently, the actuators were released by sacrificial layer (BOX layer) etching (Fig. 5d). At this releasing procedure, *Y. Fukuta* proposed to use the vapor HF technique, where vapor of hydrofluoric acid (HF) had significant role

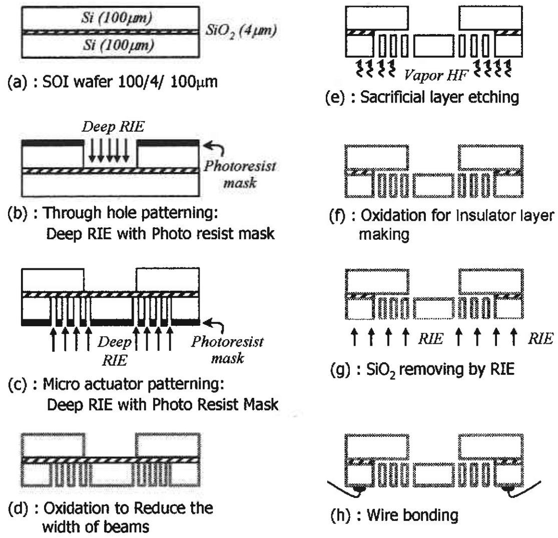

Fig. 5: Fabrication process steps of MEMS actuator

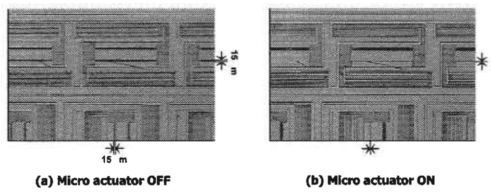

Fig. 6: Experimental results of micro actuator motion

to avoid a sticking problem and realize freestanding structures[17].

At the same time, the silicon oxide layer on the surface of the structure, in particular of the suspensions, was removed and it made possible to reduce the spring constant of the suspensions to realize lower driving voltage (Fig. 5e). After the releasing procedure, the structures were oxidized again in order to ensure electrical isolation between voltage supply pads and ground pads (Fig. 5f). Then silicon oxide layer on the surface of electrical contact pads was removed by RIE process (Fig. 5g). Finally, the structure was mounted on a printed circuit board and electrically connected by wire bonding process (Fig. 5h).

Array of micro valve-actuators functionality

Figure 6 shows an array of the micro valve-actuators realized by our fabrication process.

Almost all of the actuators have been successfully driven by electrostatic force. By using the pull-in effect of the electric voltage of 90 V, we have realized 15 μm displacement (the designed value). The system has x direction and y direction micro actuators, which makes two-dimensional motion of the conveyance.

DESIGN OF A TWO-DIMENSIONAL MICRO CONVEYANCE DEVICE

In order to realize more complex tasks of conveyance with many MEMS actuators, *Y. Fukuta* proposed to extend the previous work by developing a two-dimensional micro actuator array,

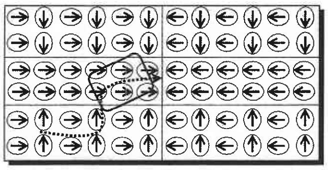

Fig. 7: MEMS actuator distributed structure

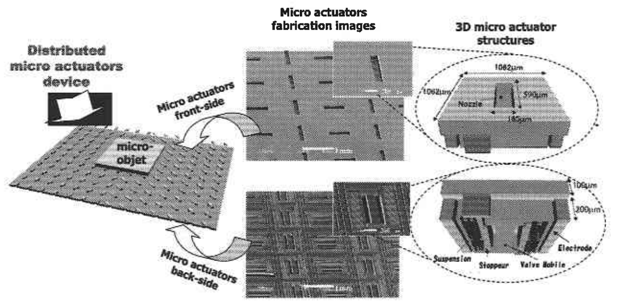

Fig. 8: Distributed micro conveyance system images

which has 560 MEMS actuators in a 35 mm × 35 mm conveyance area[16].

Two-dimensional micro conveyance design

The choice of the MEMS actuator distributed structure requires a particularly attention to achieve successfully the two-dimensional control motion. In a first approach, the distributed structure presented in the figure 7 was developed. Micro actuators arrays are well distributed to handle the micro object to converge toward the system center, whatever its original position.

Figure 8 shows the 3D structure and image of each micro actuator integrated into the distributed conveyance device. A basic cell size is approximately 1mm × 1mm. Size of the nozzle is 165 μm × 590 μm. In the bottom substrate, a movable nozzle is supported by suspension beams. Two electrodes for electrostatic force are aligned next to the movable part and fixed to the top substrate.

Movable nozzle moves left or right with the assistance of electrostatic force. Electrical short-circuit problem is avoided thanks to the stopper parts, where a movable nozzle stops before it is brought into contact with the electrode.

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EXPERIMENTAL VALIDATION OF THE MICRO CONVEYANCE DEVICE

Test bench set up

Figure 9 presents the test bench set up used to validate the two-dimensional micro conveyance system.

A centralized control of each micro actuator array was performed by a simple program in C language developed from a PC. The pneumatic micro conveyance device is assembled to a mechanical adjustment system. Interface between PC controller and MEMS actuator electrodes of device are carried out by 4 driver HV boards. Nitrogen gas was applied as an air-flow source.

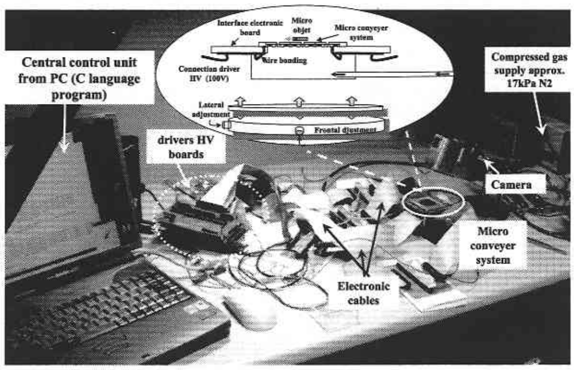
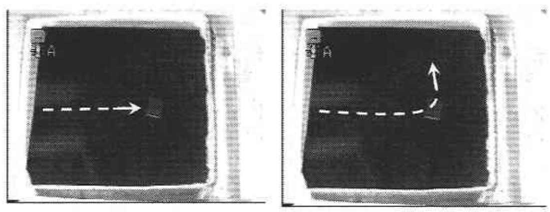


Fig. 9: Test bench of the micro conveyance system



(a) Conveyance from west to east　　(b) Conveyance from south to north

Fig.10: Experiment results of 2 D micro conveyance

Experimental results

Figure 10 shows conveyance experiment of two-dimensional systems. The object is 2.1mm *x* 4.1mm *x* 0.2mm in size, and approximately 4mg weigh. Nitrogen gas of 17kPa was applied as an air-flow source.

From obtained results, we can conclude to the feasibility of the pneumatic micro conveyance by distributed air-flow micro actuators.

Y.-A. Chapuis, a resident French CNRS researcher of *LIMMS/CNRS-IIS*, joined the project from November 2002 within *Pr. Fujita laboratory*. Cooperating with *Y. Fukuta*, they proposed new improvements based on different distributed structures of the micro conveyance device or functionality conditions as pulsed air control. These developments are now under investigation.

4. Micro manipulation by distributed Autonomous Decentralized MEMS

SMART MEMS DESIGN AND FABRICATION APPROACH

Figure 11a schematically illustrates the micro conveyance system based on the distributed ADM, also called Smart MEMS. It is

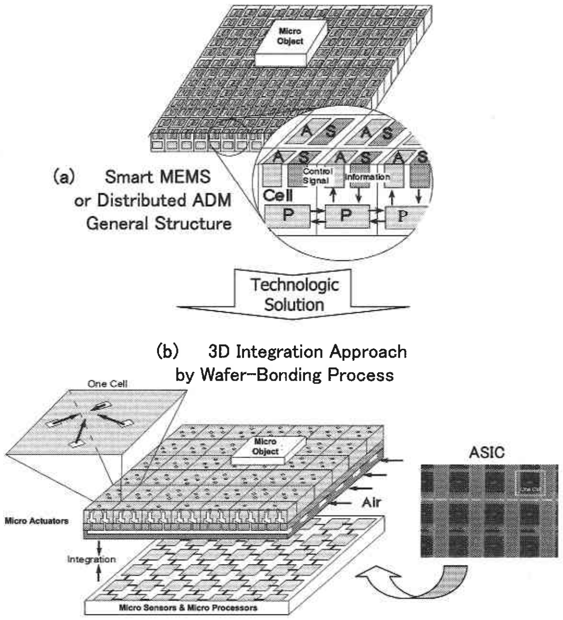


Fig. 11: Smart MEMS design approach

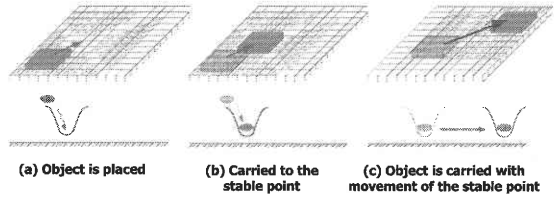


Fig 12: Concept of micro conveyance by many cells

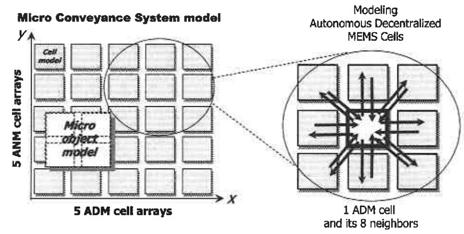


Fig 13: ADM cell control strategy

an array of micro cells, which consists of micro actuators, micro sensors, and micro processors. The cell work autonomously and cooperate each other to realize complex tasks. The micro actuators generate force to convey micro objects, micro sensors and micro processors control the system. The cells perform also the cooperation operation and work as a distributed system to recognize of a micro object.

This research had been made in respective part by *V.I. Kohlbecker* and *Y. Mita* within both *Pr. Fujita Laboratory* and *LIMMS/CNRS-IIS* of The University of Tokyo associated at the *IEMN*, Lille, France[18,19].

In the frame of this research work, we propose a 3D integration approach by wafer-bonding process to design and fabrication the Smart MEMS device, as shown in the figure 11b.

This fabrication mode allows to combine the developed MEMS actuators structure with a CMOS chip based on adapted optical micro sensors (pixels) and micro processors. A first ASIC prototype, composed of 49 cells, was already carried out by 0.8 μm-rule CMOS fabrication process and is[20].

Besides, a third wafer-bonding integrating High Voltage Divers must also be inserted between the two previous in order to drive MEMS actuators, which require at least 90 V control supply.

CONTROL METHOD TO REALIZE 2D CONVEYANCE BY MICRO ACTUATOR ARRAY

Control method concept

In some previous works, control methods to handle the developed micro conveyance device have been already achieved[16]. It has proposed using a cooperative function of arrayed micro actuators to handle an object relatively larger than the actuator component.

In this system, we first arrange the micro actuator array to direct their pointing vectors to a place in the system, to which an object is transferred (Fig.12a → Fig.12b). As the reference position given to the actuator array is moved, the micro actuators organize themselves to carry the micro object toward its final destination (Fig.12b → Fig.12c).

This control method is prospected to have following characteristics: 1) summation of forces by many actuators makes a large power, 2) since every force is directed to the center of the conveyed micro object; the object will keep its position and be robust to disturbance.

Control strategy proposal

A control strategy of the distributed ADM device was proposed by *Y.-A. Chapuis* in collaboration with L. Zhou of University Louis Pasteur of Strasbourg, France. This control strategy is based on a micro conveyance system model of 25 ADM cells, as shown in the figure 13.

The micro object model is given by a size of 2 *x* 2 cells. Model of each ADM cell should respect the following features: 1) the ADM cell can identify an micro-object which crosses it, 2) the ADM cell has its own intelligence to decide and activate to move an micro-object, 3) the ADM cell can move the micro-object in 4 transversal direction around it by activating, 4) the ADM cell can communicate with its 8 neighbor cells and know position of the micro-object and can activate them at distance, 5) the ADM cell has same neighborhood. Cell-MEMS at the edge of the device model are connected with cell-MEMS at the other end.

Finally, we established five rules of control which will govern any kind of conveyance situation, as follows:

- ***Rule 1***: Direction choose by the ADM cell should allow the

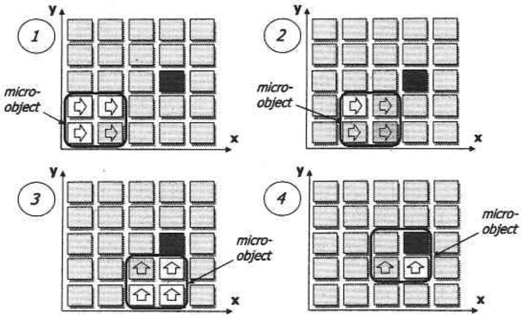


Fig 14: ADM cell control strategy

micro-object to reduce x or y longer distance with regard to its destination,

- ***Rule 2***: Only ADM cells, which are crossed by the micro-object, are activated. theirs remain inactivated,
- ***Rule 3***: Whatever the position of ADM cells with regard to the destination, activated ADM cells should always act to move the micro-object in same direction,
- ***Rule 4***: In case of conflict between Rules 1 & 3, priority will be given to Rule 3,
- ***Rule 5***: Once the micro-object reached its destination, the ADM cell crossed by the micro-object should become inactivated.

The figure 14 presents a four-steps micro conveyance example applying control rules elaborated previously. As it have been explained, each ADM cell should take action to hold the micro object to its destination

The control strategy model was validated by simulation (Altera, Quartus II) and tested on a FPGA solution (Altera, EP20K200EFC484-2X). We obtained a integration rate of hardly 2%, which is corresponded to approximatly 4000 logic cells. These optimal results are good enough to prevent a new ASIC design.

The next step of this work will be to validate the control strategy with the micro conveyance device base on distributed ADM.

5. Conclusion

MEMS technology was proposed for investigate in the field of Autonomous Decentralized Systems and their applications. Particularly, within the *Pr. Fujita laboratory* and in the frame of *LIMMS/CNRS-IIS*, studies have been made since more than ten years to develop Autonomous Decentralized MEMS, or Smart MEMS, for micro manipulation.

Recently, a pneumatic micro conveyance system that consists of an array of micro air-valves has been realized. Two-dimensional conveyances have been already demonstrated on the array of 560 micro valves, for a small silicon chip. A control method of the distributed systems was also proposed and is still under investigation in field of distributed cooperation and identification.

The collaboration within the *LIMMS/CNRS-IIS* proves advantages of this structure where both Japanese and French can provide scientific support to the other part. It provided it until now and will do it in the future, which is especially true to challenge complex field as Autonomous Decentralized MEMS for micro manipulation or for other innovate applications

Acknowledgments

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All FPGA implementations and simulations have been made in LEPSI of the Louis Pasteur University of Strasbourg, which is a LIMMS/CNRS-IIS affiliated laboratory.

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