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— *of inventorship (Rule 4.17(iv))*

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(54) Title: MICROROBOT AND MICROROBOTIC TRAIN SELF-ASSEMBLY WITH END-EFFECTORS

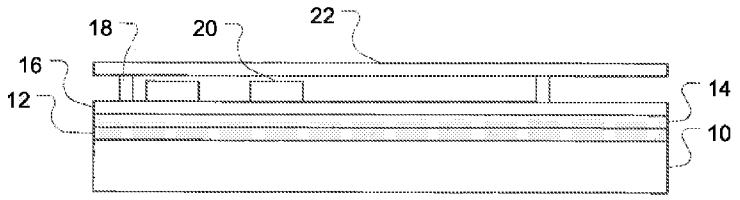


Fig. 1

(57) Abstract: A microrobot assembly system includes a substrate containing conductive traces formed into at least one holding zone and one moving zone, a diamagnetic layer on the substrate, at least two magnetic structures movable across the diamagnetic layer in response to voltages applied to the conductive traces, wherein the holding zone holds one of the magnetic structures and the moving zone allows another of the magnetic structures to attach to the magnetic structure being held. The system may include a plate spaced above the substrate and rails to guide the moving magnetic structures.

WO 2016/172217 A1

MICROROBOT AND MICROROBOTIC TRAIN SELF-ASSEMBLY WITH END-EFFECTORS

GOVERNMENT RIGHTS

[0001] This invention was made with Government support under contract HR0011-12-C-0040 awarded by Defense Advanced Research Projects Agency. The government has certain rights in this invention.

RELATED APPLICATIONS

[0002] This application claims priority to US Provisional Patent Application Nos. 62/296,638, filed February 18, 2106; 62/149,891, filed April 20, 2015; and 62/162,514, filed May 15, 2015.

[0003] This application relates to US Patent Application Nos. 14/196,720, filed March 4, 2014; and 14/177,945, filed February 11, 2014.

BACKGROUND

[0004] Microrobots, also referred to as micromanipulators, typically consist of an array of magnets that can move across a diamagnetic surface, such a graphite. A circuit substrate having conductive traces lies under the diamagnetic layer. When a controller applies voltages to the traces, the resulting magnetic fields control the movements of the microrobots. Aspects of these microrobots and associated systems are discussed in US Patent Nos. 8,593,016, 8,868,602, 8,941,270, and 6,858,184.

[0005] These microrobots provide a degree of flexibility and adaptability previously unattainable by micromanufacturing systems. In some instances, the microrobots having the ability to assemble and reconfigure themselves would provide even more flexibility in the

applications that use them. For some applications, the microrobots alone do not transmit enough force to accomplish some desired tasks. If the microrobots had the ability not only to assemble themselves into microrobots from individual magnets, but to join with other microrobots, more applications would become possible.

[0006] Another aspect of the microrobot systems involve the tools, referred to as end effectors, that attach to the microrobots. The microrobots use the end effectors to manipulate other items, often in pick and place manufacturing systems. In current systems, some of the pickup end effectors do not hold the item effectively. Typically, the picking operation for small size objects uses wetting, but simpler wetting surfaces tend to dry out and one cannot easily determine if the end effector still has water. Other issues may arise because of surface rigidity.

SUMMARY

An embodiment includes a microrobot assembly system having a substrate containing conductive traces formed into at least one holding zone and one moving zone, a diamagnetic layer on the substrate, and at least two magnetic structures movable across the diamagnetic layer in response to voltages applied to the conductive traces, wherein the holding zone holds one of the magnetic structures and the moving zone allows another of the magnetic structures to attach to the magnetic structure being held.

Another embodiment is a microrobot including an array of magnets forming a body of a microrobots, an end effector having a capillary, and a wettable tip.

Another embodiment is a microrobot system including at least two microrobots, each microrobot having a front connector and a back connector and a tool end effector, wherein a first microrobot has a front connector connected to a back connector of a second microrobot, and an implement having a magnetic drive forming a forward path and a return path.

Another embodiment is a microrobot assembly system having a substrate containing at least one conductive trace, a diamagnetic layer on the substrate, at least one spacer on the diamagnetic layer having a predetermined height, a plate on the spacers, and at least two magnets movable across the diamagnetic layer when voltage is applied to the at least one conductive trace, the magnets having a height less than the predetermined height.

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] Figure 1 shows a side view of a microrobot assembly system;

[0008] Figure 2 shows a top view of an embodiment of a microrobot assembly system.

[0009] Figures 3-4 show a top view of an embodiment of a microrobot assembly system.

[0010] Figure 5 shows a top view of an embodiment of a microrobot assembly system.

[0011] Figures 6-8 show an embodiment of a microrobot train assembly and application system.

[0012] Figure 9 shows an embodiment of a wetting end effector.

DETAILED DESCRIPTION OF THE EMBODIMENTS

[0013] Figure 1 shows a side view of a microrobot assembly system. In this embodiment, the microrobot assembly system includes a substrate 10. The substrate 10 may consist of a typical printed circuit board (PCB), ceramic, flex circuits, etc. The substrate has at least one layer of conductive traces such as 12. Typically, the substrate may contain multiple layers of conductive traces such as 12 and 14. When a controller applies voltage to these traces, the current flowing in the traces generates electromagnetic fields that can be used to control magnets.

[0014] The magnets, such as 20, used here are single-polarity magnets, meaning that they have a single direction of magnetization, that become microrobots when joined together. As

will be discussed later, the microrobots can form trains of microrobots. This discussion refers to any of these structures as magnetic structures.

[0015] The substrate 10 has a diamagnetic layer 16 that allows the magnets to either move across the surface of the substrate with the diamagnetic layer, or even 'float' or levitate above the surface because of the magnetic fields. As will be discussed in more detail further, the magnets and microrobots can move vertically, so the plate 22 restrains the motion to prevent one of the magnets or microrobots from getting on top of the other. The plate 22 lies above the substrate a distance on spacers such as 18 sufficient to allow the magnets such as 20 to fit underneath the plate. The plate may consist of glass, aluminum, copper or any other planar material. The use of a metal plate may assist with damping eddy currents.

[0016] The basic system includes the substrate with conductive traces, a diamagnetic layer, the plate and the magnets that eventually form the microrobots. Several different configurations of the system are possible. In one embodiment, the spacers such as 18 may form guides to allow the magnets to be directed into an assembly area, or incubator. In the embodiment of Figure 2, the incubator is formed by a mechanical stop 26, and two guides 24 and 28. Guide 24 acts as an error correcting guide that allows the magnet to be driven into the guide 24 and towards the mechanical stop 26. The magnets 20 and 30 have opposite directions of polarization. The guides may also act as the spacers. In one embodiment, the guides may consist of 500 micron thick spacers for 400 micron thick magnets.

[0017] During assembly, the currents in the traces drive a magnet such as 32 into the guide rail 24 and down towards the mechanical stop 26. The magnet 32 encounters magnets 30 and 20 and connects to them magnetically, forming a microrobot. Once the microrobot has the desired number of magnets, the system drives out of the incubator area as shown by the outgoing arrow. One embodiment forms a microrobot of magnets of 1.4 mm by 1.4 mm by

0.4 mm magnets controllable in three or more degrees of freedom. Microrobots of greater complexity can be formed with additional magnets, end effectors, etc.

[0018] Figures 3 and 4 show view of an alternative embodiment. This embodiment also includes the substrate 10, the plate 22. Spacers, not shown in Figures 3 and 4, can hold the plate 22 the desired offset from the substrate 10. In this embodiment the conductive traces within the substrate, which provide the electrically controllable magnetic forces when driven with electrical current, are divided into independently controlled zones such as 40 and 42. In this embodiment the zone 40 constitutes a holding zone, and zone 42 a moving zone. In some embodiments with suitable magnet sizes (such as 1.4 x 1.4 x 0.4 mm magnets) plate 22 can be eliminated if the geometry is stable enough to prevent flipping one magnet on top of another. However, plate 22 generally increases reliability as subtle variations in magnets or surface interactions over time during motion may cause a flip. Zone 40 can also move magnets and magnetic arrays using its conductive traces, but it is referred to as a holding zone because during assembly its primary function is to hold the magnets in position. A starting structure, such as a 2 x 1 array to a position near the boundary between zone 40 and the zone 42, but still within the holding zone 40. By keeping some parts of the starting structure within the holding zone, the magnetic forces exerted by holding zone 40 may provide sufficient holding against the impact of incoming magnets.

[0019] As shown in Figures 3 and 4, the guides 44 and 46 provide direction to the magnets to form the new microrobot. In this embodiment, the starting structure consists of magnets 20 and 30 and magnet 48 is to be added to the structure. The magnet 48 is driving into the guide 44 and then along the guide 44 to magnetically attach to the starting structure. As shown in Figure 4, the magnet could also be driven along the guide 46 into the structure that now consists of magnets 48, 30 and 20. One should note that the guides 44 and 46 may both be

used or only one. If the adding magnet or other added structure are well controlled, the guides may not be needed. Once assembled, the microrobot drives out of the holding zone and into the moving zone.

[0020] Figure 5 shows an assembly system in which multiple magnets can be assembled at once rather than individually. This also increases the controllable assembly force. The structure 52 has alternating pole magnets. The gray magnets are magnets with north poles up and the white magnets are south poles up. The structure 52 has two north poles adjacent to the south pole where the structure 54 is to be added. This causes an energy barrier that must be overcome to push a north pole magnet against the 2 nearby north poles before it can snap to the south pole magnet. In some systems, the driving force may be insufficient to achieve this with a single magnet, but using two or more magnets in structure 54 may create enough force. In this manner, magnets can assemble into microrobots. In addition, microrobots can form themselves into microrobot trains.

[0021] Similar to microrobots that need extra force to snap to other structures, some applications may need enough force to perform certain tasks. In one example, the microrobots may need more force to insert an end effector into tissue such as to perform a biopsy or other such task. One should note that while this particular application involves an insertable application along a catheter, these are merely examples and are not intended to limit the scope of the embodiments.

[0022] In Figure 6, a catheter 70 would have a flex circuit, not shown, similar to the substrate and traces shown in Figure 1. The catheter has sufficient room to allow two paths, a forward path 74 and a return path 72. A first microrobot 60 has a front connector 66 and a rear connector 64. The microrobot 60 also has an end effector arm 62 and a tool 68. The tool 68 may consist of a needle, retrieval end effector, or other type of biopsy tool.

[0023] The microrobot 60 forms a train with other microrobots by means of the front and back connectors. The connectors in this embodiment consist of an eye loop 66 and a hook 64. Connectors may also be magnetic or other means known in the prior art of small connectors. The microrobots can connect themselves together to form the train. Figure 7 shows an example of how one microrobot can disconnect itself from the train. By moving slight backwards, as shown in Figure 7, the hook releases from the eye loop. As shown in Figure 8, the microrobot 60 then moves up to the return path 72 and the remainder of the train then moves up into the space previously occupied by microrobot 60. This allows the system to replace one robot and one robot function with another very quickly, without withdrawing the entire instrument from the catheter each time.

[0024] With the mechanically linked robots, the combined microrobots can achieve a higher force than they can individually. The amount of force needed the number of microrobots needed in the train, based on the amount of force each microrobot can exert individually to add to the total train force. The region 76 of the forward and return paths 72 forms a control zone with multiple degrees of freedom. One variation would be to have multiple microrobots in the return path.

[0025] In addition to microrobot trains that can have biopsy end effectors, some end effectors use wetting to perform pick and place of items. One embodiment performs pick and place of small pieces of material, referred to as platelets. Issues arise with using wetting. Simple wetting surface can work, but dry out relatively quickly, and it is not easy to determine whether or not they have liquid. In addition, other surfaces are rigid and then do not wet the pick object as well as desired for reliable gripping.

[0026] An embodiment of an end effector that achieves more reliable wetting and has easily determinable liquid levels is shown in Figure 9. The microrobot 80 has a capillary 82 that

acts as a reservoir of liquid and will typically be transparent to allow one to determine the amount of liquid in the reservoir as well as being easily fillable. In one preferred embodiment, the capillary 82 was a polyimide capillary with a diameter of 1.5 mm and length of 5-10 mm. The capillary length is normally chosen so that the liquid stays in the capillary (in liquid communication with end effector 84) in all robot orientations. In another preferred embodiment, the length is chosen relative to the diameter so that liquid is held in while the microrobot is in a horizontal orientation, but drops come out when the microrobot is tilted vertically, such as while operating on a flex circuit known in the prior art. In this preferred embodiment, the microrobot can therefore dispense liquid drops on demand, such as for watering plants or other automation functions where drop dispensing is desired.

[0027] The capillary reservoir also allows the microrobot to pick and place multiple objects before needing to be refilled. The end effector may be porous or other absorptive material that can absorb liquids from the reservoir. These materials also provide a slight negative pressure relative to atmosphere on the liquid relative to atmosphere due to wetting of a large surface. This slight negative pressure prevents excessive water from flowing, such as on the object being picked up. The end effector 84 may consist of metal meshes, porous materials such as porous polyethylene, sponges, brushes, hydrogels and other high surface area wetting surfaces.

[0028] In this manner, one can assemble microrobots from magnets, and microrobot trains from multiple microrobots. The configuration of the microrobots and the microrobot trains depends upon the desired application. For example, the configuration of the microrobots may depend upon the size desired, or the number of poles desired. The configuration of the trains may depend upon the desired amount of force to be applied to a surface. The end effector

used may include a porous or other absorptive material attached to a capillary that acts a reservoir of liquid.

[0029] It will be appreciated that variants of the above-disclosed and other features and functions, or alternatives thereof, may be combined into many other different systems or applications. Various presently unforeseen or unanticipated alternatives, modifications, variations, or improvements therein may be subsequently made by those skilled in the art which are also intended to be encompassed by the following claims.

WHAT IS CLAIMED IS:

1. A microrobot assembly system, comprising:

a substrate containing at least one conductive trace;

a diamagnetic layer on the substrate;

at least one spacer on the diamagnetic layer having a predetermined height;

a plate on the spacers; and

at least two magnets movable across the diamagnetic layer when voltage is applied to the at least one conductive trace, the magnets having a height less than the predetermined height.

2. The assembly system of claim 1, wherein the plate comprises one of copper, aluminum and glass.

3. The assembly system of claim 1, wherein the plate is spaced above the diamagnetic layer a predetermined height.

4. The assembly system of claim 1, wherein the at least one conductive trace comprises at least one conductive trace formed into two control zones, a holding zone and a moving zone.

5. The assembly system of claim 4, wherein the plate is on the diamagnetic layer adjacent a boundary between the two control zones.

6. The assembly system of claim 5, further comprising at least one guide arranged to direct the magnets from the moving zone to the holding zone.

7. The assembly system of claim 1, wherein the at least two magnets comprise at least three magnets movable into the holding zone to form one of a one-dimensional array and a two-dimensional array.

8. The assembly system of claim 1, further comprising a mechanical stop.

9. The assembly system of claim 8, further comprising a guide arranged adjacent the mechanical stop.

10. The assembly system of claim 9, wherein the spacers are the guides.

11. A microrobot system, comprising:

at least two microrobots, each microrobot having a front connector and a back connector and a tool end effector, wherein a first microrobot has a front connector connected to a back connector of a second microrobot; and

an implement having a magnetic drive forming a forward path and a return path.

12. The system of claim 11, wherein the tool effector comprises a retrieval effector.

13. The system of claim 12, wherein the retrieval effector comprises a biopsy needle.

14. The system of claim 11, wherein the at least two microrobots comprises a number of microrobots having a combined individual force to apply a predetermined amount of total force.

15. The system of claim 11, wherein the front connector comprises an eye loop and the rear connector comprises a hook.

16. The system of claim 11, wherein the front and back connectors comprise an electrolaminate clamp connector.

17. The microrobot system of claim 11, wherein the implement comprises a catheter.

18. The microrobot system of claim 11, wherein the magnetic drive comprises a flex circuit having conductive traces.

19. A microrobot, comprising:

an array of magnets forming a body of a microrobots; and

an end effector having a capillary; and

a wettable tip.

20. The microrobot of claim 19, wherein the wettable tip comprises one of a metal mesh, porous polyethylene, sponges, brushes, and hydrogels.

21. A microrobot assembly system, comprising:

a substrate containing conductive traces formed into at least one holding zone and one moving zone;

a diamagnetic layer on the substrate; and

at least two magnetic structures movable across the diamagnetic layer in response to voltages applied to the conductive traces, wherein the holding zone holds one of the magnetic structures and the moving zone allows another of the magnetic structures to attach to the magnetic structure being held.

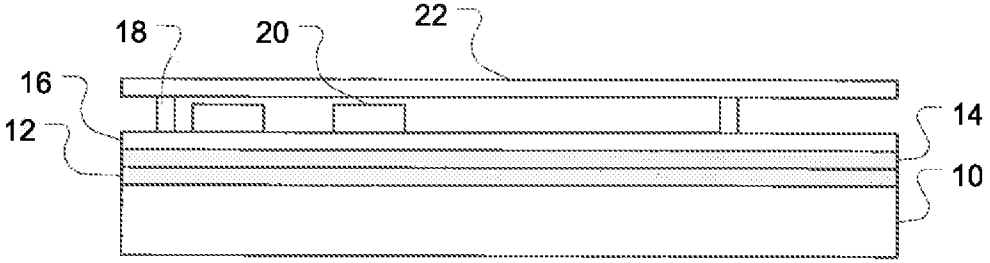


Fig. 1

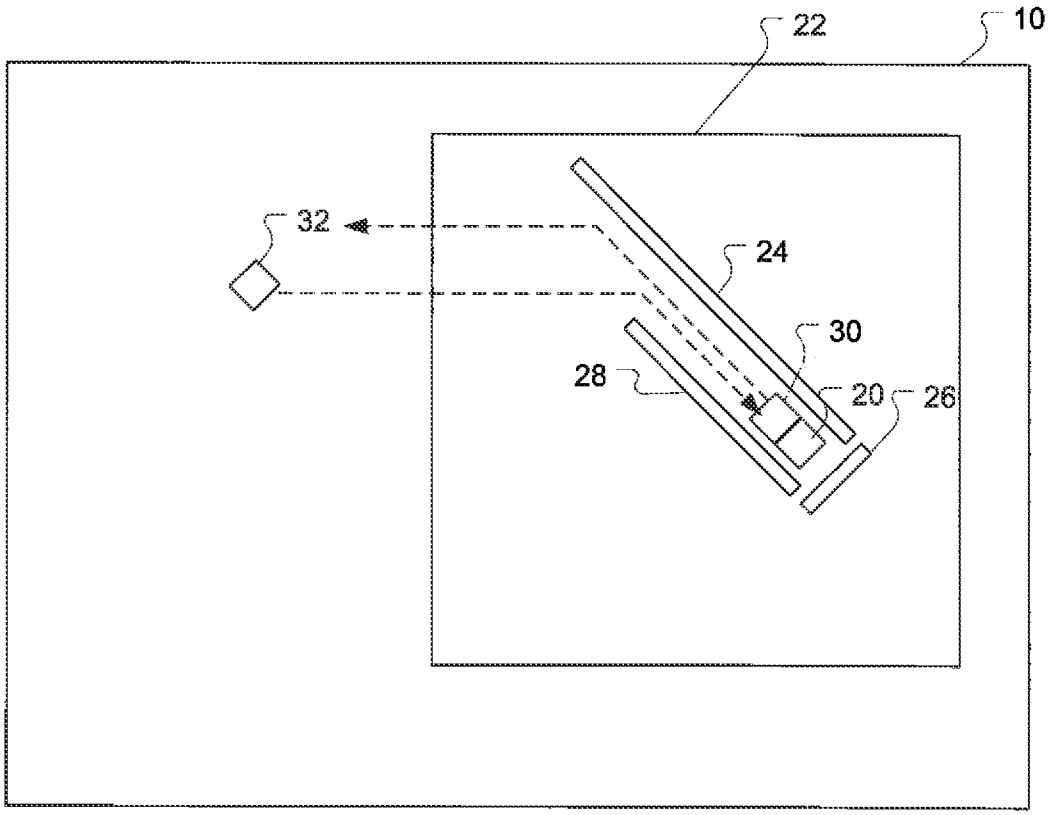


Fig. 2

Fig. 3

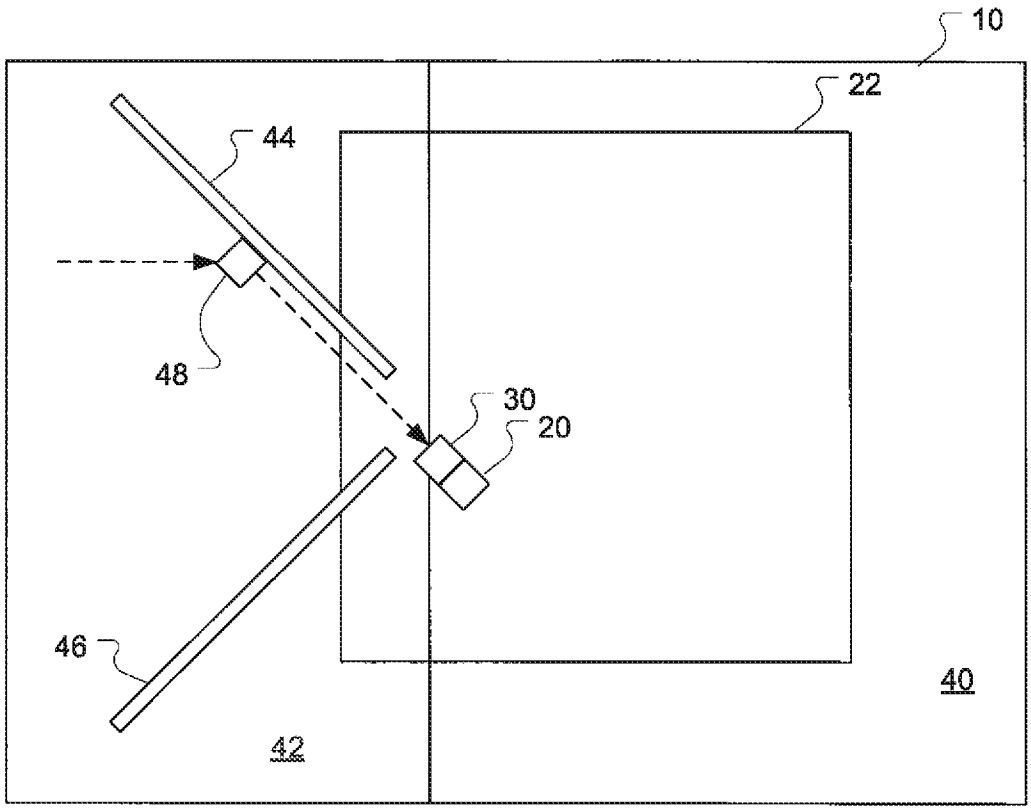


Fig. 4

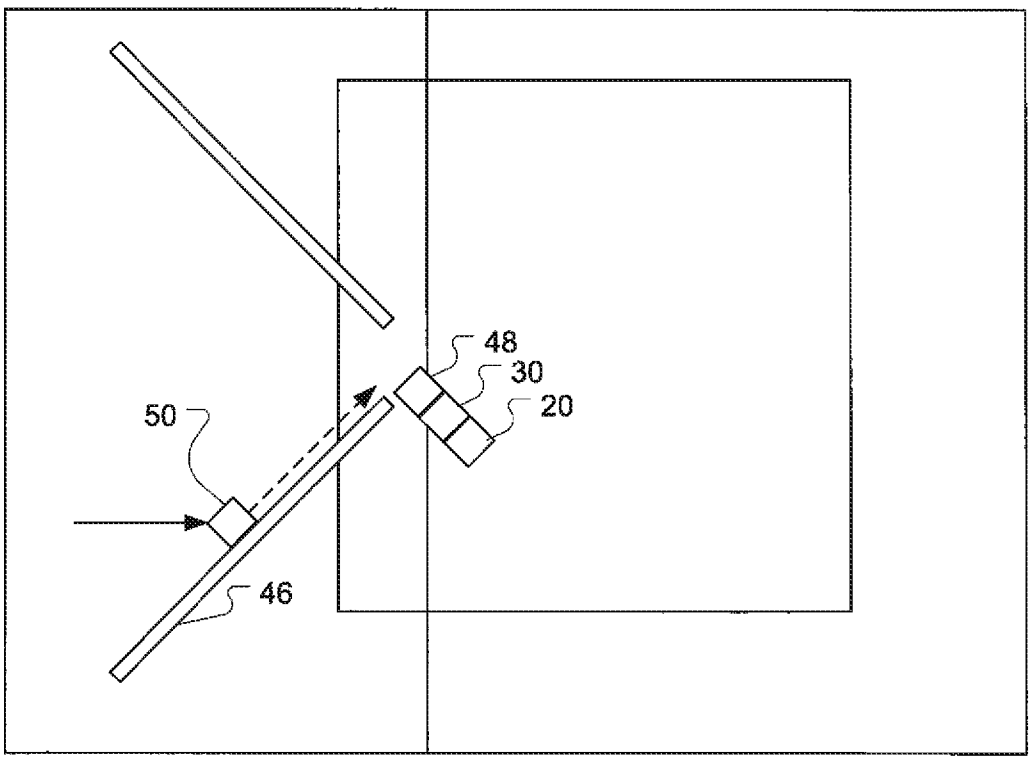


Fig. 5

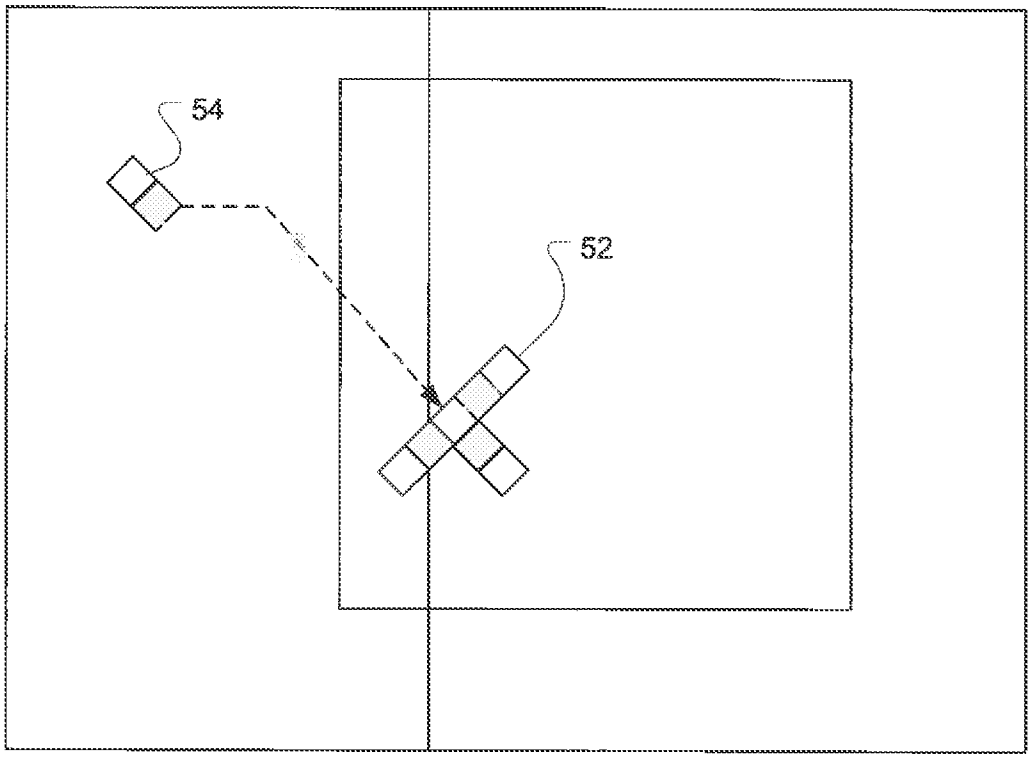


Fig. 6

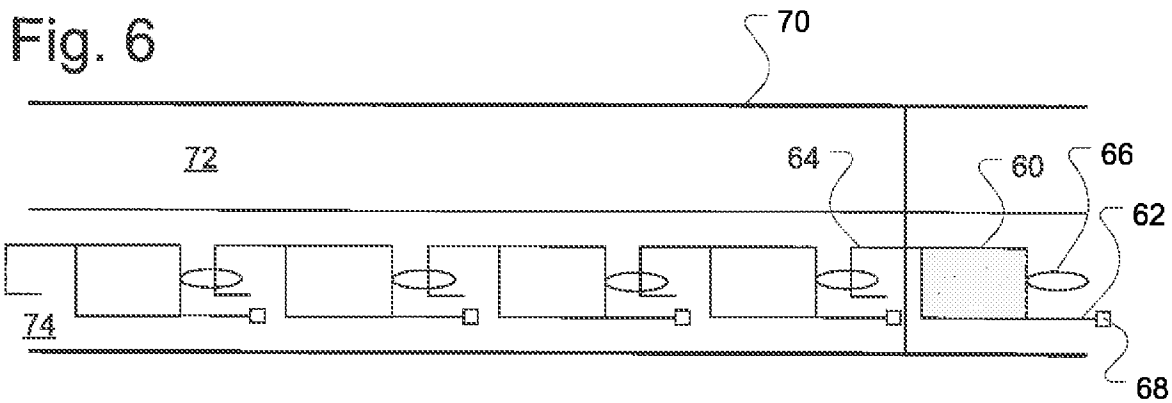


Fig. 7

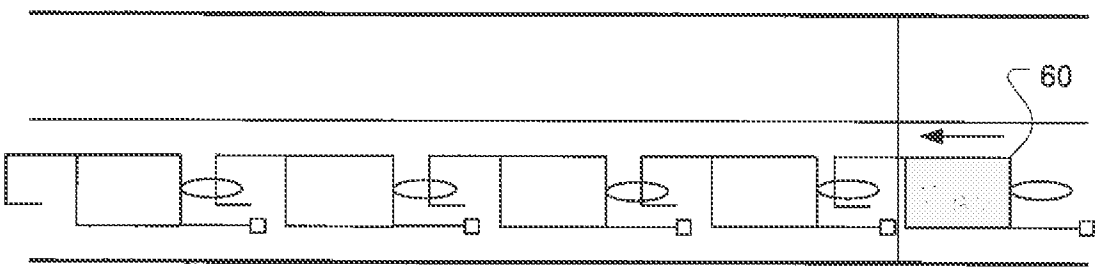


Fig. 8

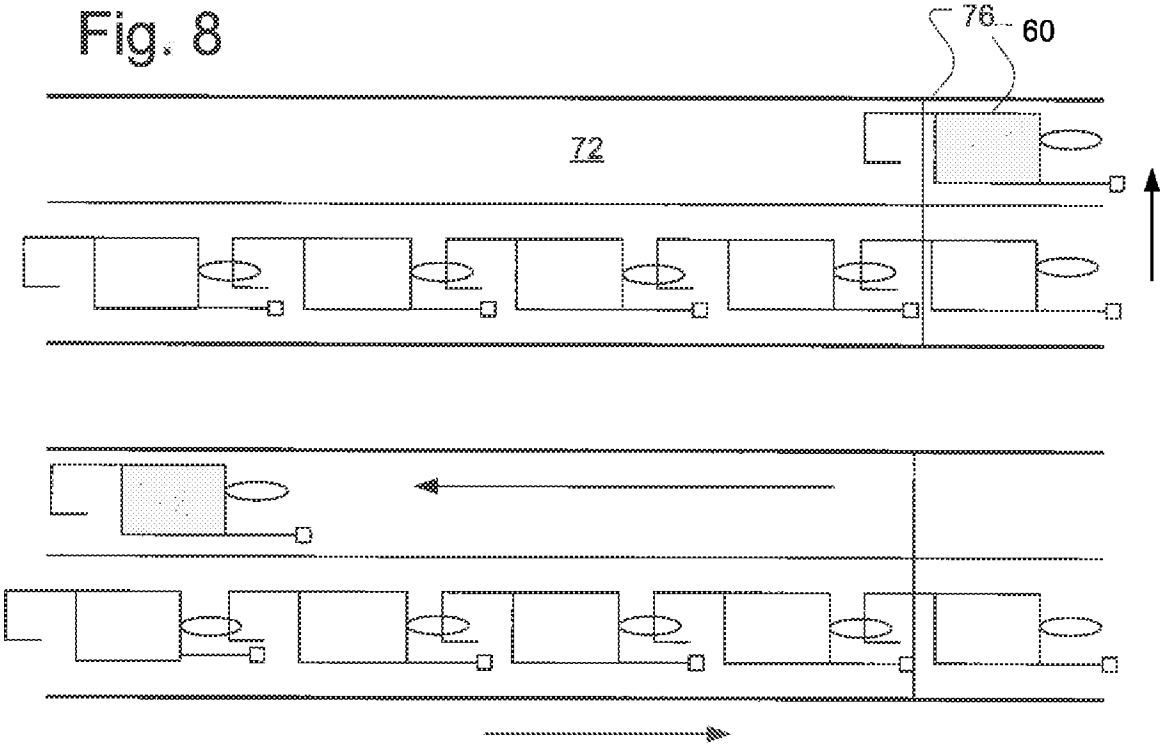
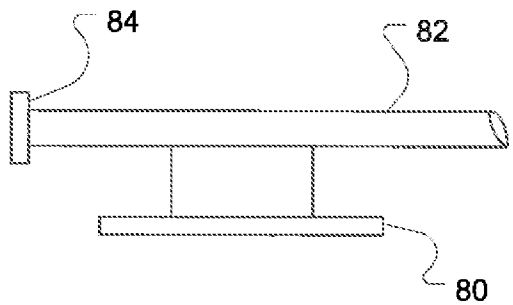


Fig. 9



INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2016/028448

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3 ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:
See supplemental page

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☒ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:
1-10, 21

Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.

☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.

☐ No protest accompanied the payment of additional search fees.

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2016/028448

A. CLASSIFICATION OF SUBJECT MATTER
IPC(8) - H01F 7/127; B23P 19/04; H01F 7/02; H01F 7/04; H02N 15/00 (2016.01)
CPC - H01F 7/0236; B23P 19/04; H01F 7/0242; H01F 7/0247; H01F 7/04; H01F 7/127 (2016.05)
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC - B23P 19/04; H01F 7/02; H01F 7/04; H01F 7/127; H02N 15/00
CPC - B23P 19/04; H01F 7/0236; H01F 7/0242; H01F 7/0247; H01F 7/04; H01F 7/127; H02N 15/00

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
USPC - 29/428; 29/467; 29/709; 29/719; 29/744; 29/810; 310/12.050; 310/154.290 (keyword delimited)

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
Orbit, Google Patents, Google Scholar
Search terms used: microbot, trace, magnet, holding, move, spacer, diamagnetic, stop, assembly, height, guide, zone

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 2014/0217835 A1 (SRI INTERNATIONAL) 07 August 2014 (07.08.2014) entire document	1-10, 21
Y	US 5,193,267 A (SATOH et al) 16 March 1993 (16.03.1993) entire document	1-10
Y	US 2014/0123461 A1 (WHITESIDS et al) 08 May 2014 (08.05.2014) entire document	7, 21
A	US 2014/0225694 A1 (CARNEGIE MELLON UNIVERSITY) 14 August 2014 (14.08.2014) entire document	1-10, 21

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
12 August 2016	13 SEP 2016
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INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2016/028448

Continued from Box No. III Observations where unity of invention is lacking

This application contains the following inventions or groups of inventions which are not so linked as to form a single general inventive concept under PCT Rule 13.1. In order for all inventions to be examined, the appropriate additional examination fees must be paid.

Group I, claims 1-10,21, drawn to a microrobot assembly system.
Group II, claims 11-18, drawn to a microrobot system.
Group III, claims 19-20, drawn to a microrobot.

The inventions listed as Groups I, II and III do not relate to a single general inventive concept under PCT Rule 13.1 because, under PCT Rule 13.2, they lack the same or corresponding special technical features for the following reasons: the special technical feature of the Group I invention: a substrate containing at least one conductive trace; a diamagnetic layer on the substrate; and at least two magnets movable across the diamagnetic layer when voltage is applied to the at least one conductive trace as claimed therein is not present in the invention of Groups II and III. The special technical feature of the Group II invention: wherein a first microrobot has a front connector connected to a back connector of a second microrobot; and an implement having a magnetic drive forming a forward path and a return path as claimed therein is not present in the invention of Groups I or III. The special technical feature of the Group III invention: a capillary; and a wettable tip as claimed therein is not present in the invention of Groups I or II.

Groups I, II and III lack unity of invention because even though the inventions of these groups require the technical feature of a microrobot, comprising: an array of magnets, this technical feature is not a special technical feature as it does not make a contribution over the prior art.

Specifically, US 2014/0225694 A1 (CARNEGIE MELLON UNIVERSITY) 14 August 2014 (14.08.2014) teaches a microrobot (Para. 5), comprising: an array of magnets (Para. 4).

Since none of the special technical features of the Group I, II or III inventions are found in more than one of the inventions, unity of invention is lacking.