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(54) **SWITCHABLE FLUIDIC DEVICE**

(71) Applicant: **Facebook Technologies, LLC**, Menlo Park, CA (US)

(72) Inventors: **Jack Lindsay**, Seattle, WA (US); **Sean Jason Keller**, Kirkland, WA (US); **David R. Perek**, Bellevue, WA (US); **Tristan Thomas Trutna**, Seattle, WA (US); **Nicholas Roy Corson**, Mukilteo, WA (US); **Raymond King**, Redmond, WA (US)

(73) Assignee: **Facebook Technologies, LLC**, Menlo Park, CA (US)

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F15C 3/04 (2006.01)
(Continued)

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CPC ***F15C 3/04*** (2013.01); ***F16K 7/18*** (2013.01); ***F16K 31/12*** (2013.01); ***G06F 3/016*** (2013.01); *G06F 3/014* (2013.01)

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(Continued)

(56) **References Cited**

U.S. PATENT DOCUMENTS

2,715,009 A * 8/1955 Beekley F16K 31/126 251/335.2
3,549,118 A * 12/1970 Bluder F16K 31/165 251/303
(Continued)

FOREIGN PATENT DOCUMENTS

EP 3351839 A2 7/2018
KR 10-2016-0098056 A 8/2016
(Continued)

OTHER PUBLICATIONS

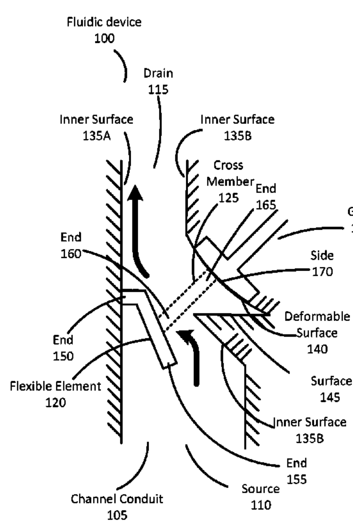
European Partial Search Report, European Application No. 18151564.4, dated Jul. 17, 2018, 17 pages.
(Continued)

Primary Examiner — John Bastianelli
(74) *Attorney, Agent, or Firm* — Fenwick & West LLP

(57) **ABSTRACT**

A fluidic device controls fluid flow in a channel conduit from a fluid entrance to a fluid exit. In some embodiments, the fluidic device comprises the channel conduit, a flexible element, a cross member, and a gate. The channel conduit is bounded by an inner surface that includes a protrusion. The flexible element is coupled to the inner surface of the channel conduit on a different side of the inner surface as the protrusion. The cross member has a first end that is coupled to a deformable surface that is part of the inner surface of the channel conduit and a second end that is coupled to the flexible element. The gate is configured to deform the deformable surface in accordance with a fluid pressure at the gate. An amount of deformation imparted by the gate controls a position of the flexible element via the cross member.

16 Claims, 3 Drawing Sheets



(51) **Int. Cl.**
F16K 7/18 (2006.01)
G06F 3/01 (2006.01)

(58) **Field of Classification Search**
USPC 251/58, 61, 228, 298, 336–337, 902
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

3,951,168	A *	4/1976	Roberts	F16K 7/18 137/625.28
5,078,363	A *	1/1992	Gregory	F16K 1/24 251/144
6,406,605	B1	6/2002	Moles	
6,474,623	B1 *	11/2002	Davies	F16K 31/1655 251/228
8,922,355	B2	12/2014	Kusuura	
2003/0196695	A1	10/2003	O'Connor et al.	
2006/0058740	A1	3/2006	Cise et al.	
2010/0180970	A1	7/2010	Welle	
2012/0039770	A1	2/2012	Namkoong et al.	
2014/0130920	A1	5/2014	Fernandes et al.	
2014/0134001	A1	5/2014	Uchida et al.	

FOREIGN PATENT DOCUMENTS

WO	WO 89/05417	A1	6/1989
WO	WO 2016/205143	A1	12/2016

OTHER PUBLICATIONS

Eddington, D. et al., "Flow Control with Hydrogels," Advanced Drug Delivery Reviews, Feb. 10, 2004, pp. 199-210, vol. 56, No. 2.
Frank, P. et al., "Integrated Microfluidic Membrane Transistor Utilizing Chemical Information for On-Chip Flow Control," PLOS One, Aug. 29, 2016, e0161024, 17 pages, vol. 11, No. 8.
Yu, Q. et al., "Responsive Biomimetic Hydrogel Valve for Microfluidics," Applied Physics Letters, Apr. 23, 2001, pp. 2589-2591, vol. 78, No. 17.
PCT International Search Report and Written Opinion, PCT Application No. PCT/US2017/064683, dated Mar. 30, 2018, 19 pages.
Devaraju, N.S.G.K. et al., "Pressure Driven Digital Logic in PDMS Based Microfluidic Devices Fabricated by Multilayer Soft Lithography," Lab Chip, The Royal Society of Chemistry, 2012, pp. 4809-4815, vol. 12.
PCT International Search Report, PCT Application No. PCT/US2017/052048, dated May 23, 2018, 18 pages.
European Partial Search Report, European Application No. 18158349.3, dated Sep. 20, 2018, 17 pages.
Mohan, R. et al., "Design Considerations for Elastomeric Normally Closed Microfluidic Valves," Sensors and Actuators B: Chemical: International Journal Devoted to Research and Development of Physical and Chemical Transducers, Sep. 17, 2011, pp. 1216-1223, vol. 160, No. 11.
Perdigones, F.A. et al., "Correspondence Between Electronics and Fluids in MEMS: Designing Microfluidic Systems Using Electronics," IEEE Industrial Electronics Magazine, Dec. 1, 2014, pp. 6-17, vol. 8, No. 4.

* cited by examiner

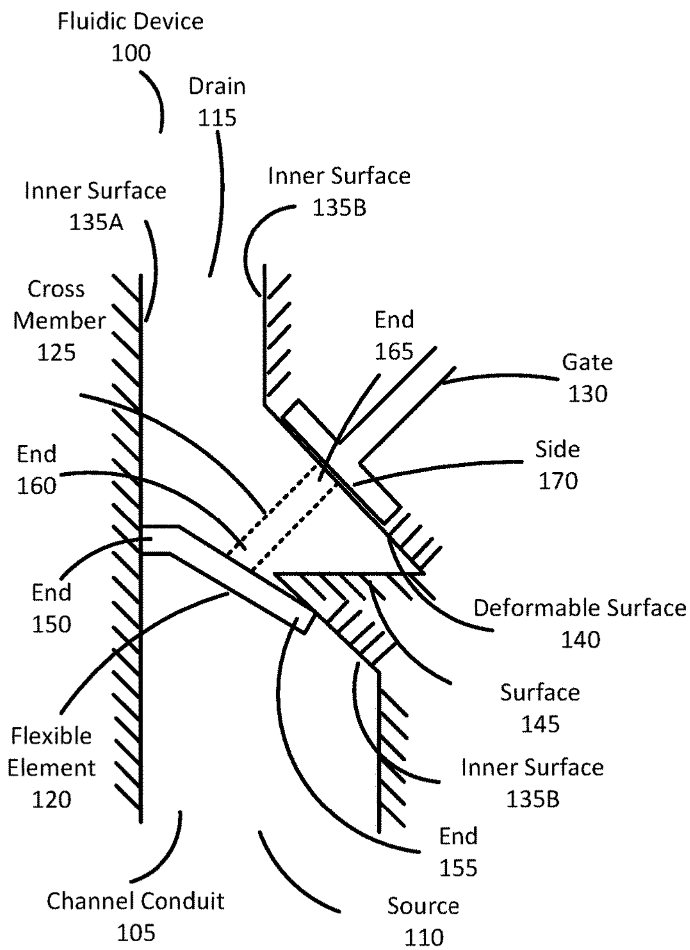
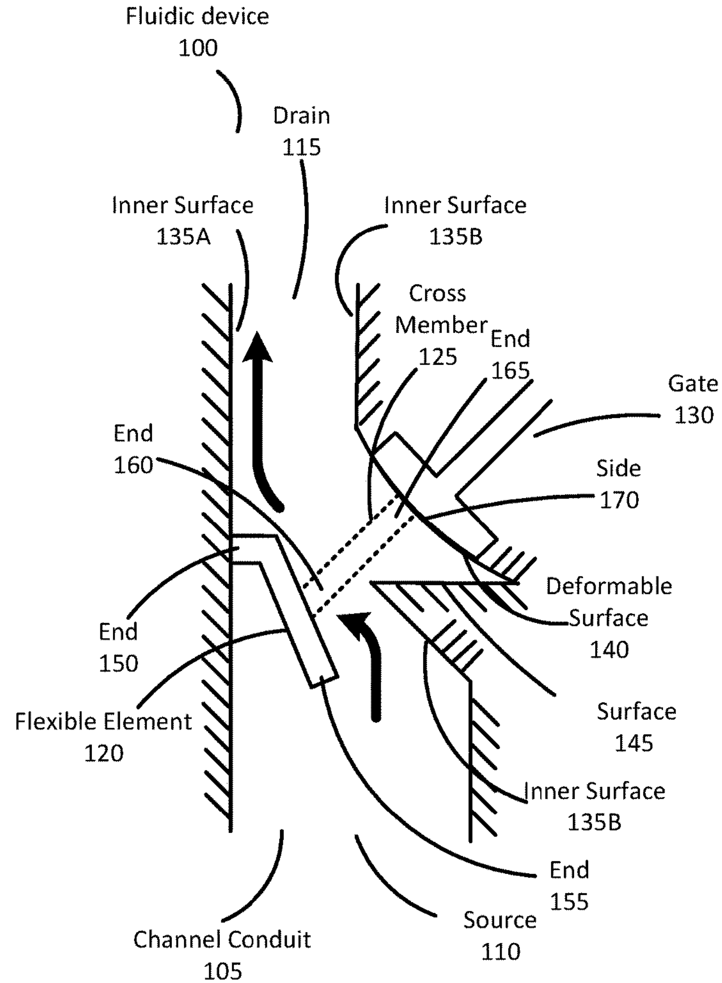

Fluidic Device
100
Drain
115
Inner Surface
135A
Inner Surface
135B
Cross
Member
125
End
165
Gate
130
Side
170
End
160
End
150
Deformable Surface
140
Surface
145
Flexible
Element
120
Inner Surface
135B
End
155
Channel Conduit
105
Source
110

FIG. 1A


Fluidic device
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Side
170
Deformable
Surface
140
End
150
Surface
145
Flexible Element
120
Inner Surface
135B
End
155
Channel Conduit
105
Source
110

FIG. 1B

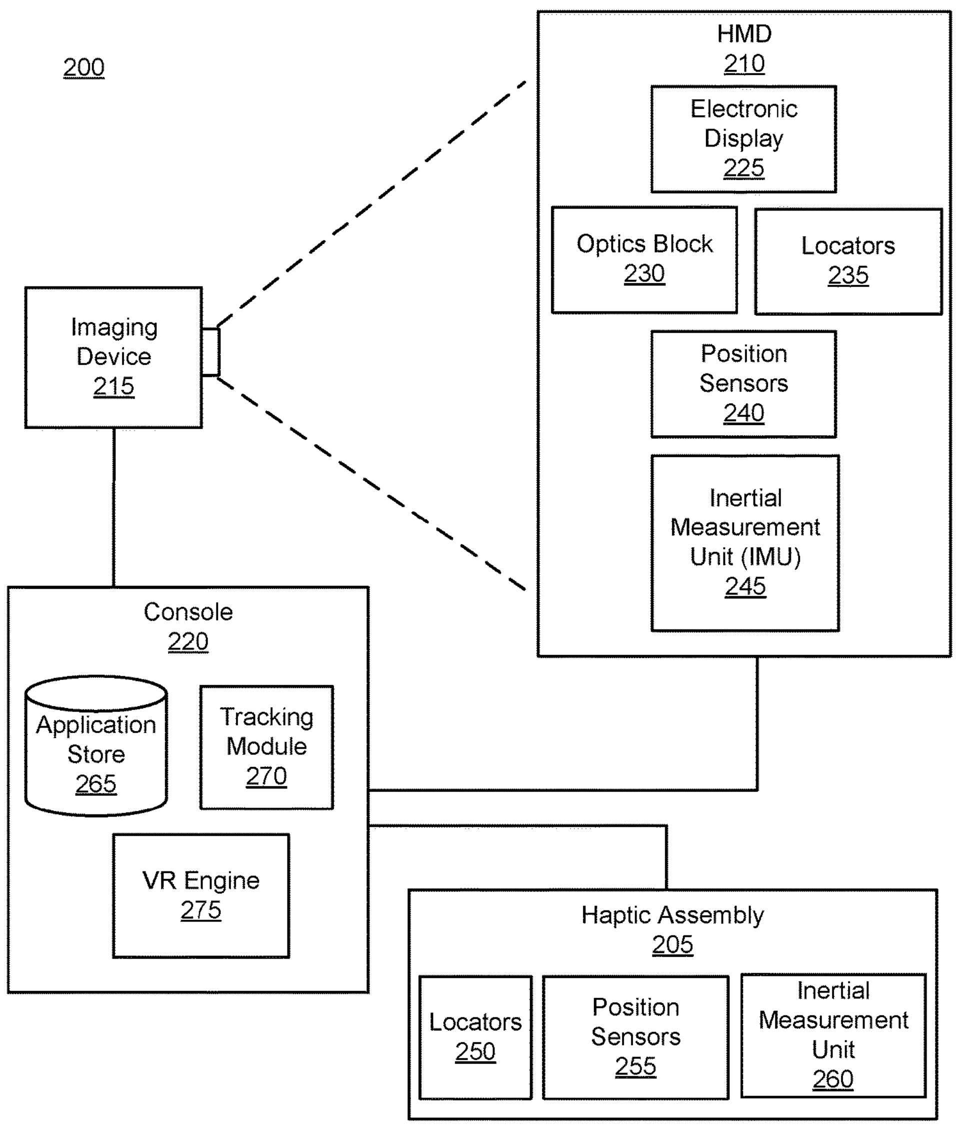
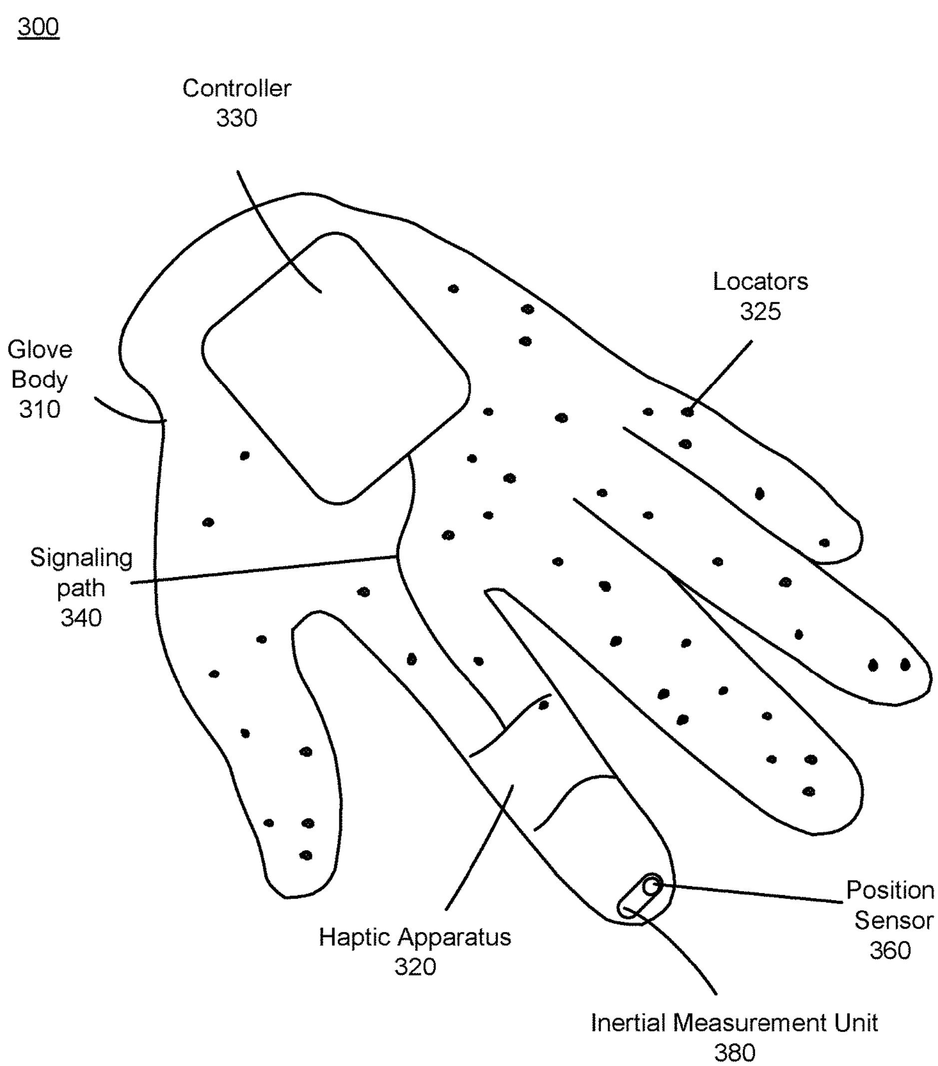

200
HMD
210
Electronic
Display
225
Optics Block
230
Locators
235
Position
Sensors
240
Inertial
Measurement
Unit (IMU)
245
Imaging
Device
215
Console
220
Application
Store
265
Tracking
Module
270
VR Engine
275
Haptic Assembly
205
Locators
250
Position
Sensors
255
Inertial
Measurement
Unit
260

FIG. 2



300
Controller
330
Locators
325
Glove
Body
310
Signaling
path
340
Haptic Apparatus
320
Position
Sensor
360
Inertial Measurement Unit
380

FIG. 3

SWITCHABLE FLUIDIC DEVICE

CROSS REFERENCE TO RELATED APPLICATIONS

This application claims benefit of U.S. Provisional Patent Application Ser. No. 62/452,242, filed Jan. 30, 2017, which is hereby incorporated by reference in its entirety.

BACKGROUND

The present disclosure generally relates to fluidic devices for head-mounted displays (HMD) and more specifically to using fluidic devices in virtual reality systems.

Virtual reality (VR) is a simulated environment created by computer technology and presented to a user, such as through a VR system. In some VR systems wearable devices (e.g., glove) allow a user to interact with virtual objects. Circuitry on such wearable devices can be complex, bulky, and in some cases heavy. As a result, conventional wearable devices can detract from a user's experience with a VR system.

SUMMARY

Embodiments of the disclosed invention include fluidic devices used in VR, augmented reality (AR) systems, and/or mixed reality (MR) systems. Fluidic devices are fluid handling devices that function analogous to electronic devices (e.g., an electrical transistor, an electrical diode, a resistor, a capacitor, etc.). For example, a fluidic device may be designed such that it operates as a fluidic transistor. Additionally, fluidic devices are composable, meaning that fluidic devices may be coupled together to form a composite fluidic device (e.g., a decoder). In some embodiments, groups of fluidic devices are coupled together to act as controllers for a haptic apparatuses on wearable devices (e.g., haptic gloves) for a VR system.

A fluidic device generally includes a channel that includes an input (e.g., a source) and an output (e.g., a drain). The channel directs a fluid (e.g., liquid or gas) from the input to the output. The fluidic device also includes a gate that affects the flow of fluid in the channel. For example, in some embodiments, once a threshold gate pressure is achieved (i.e., a high pressure state), the gate may restrict the fluid flow in the channel. In alternate embodiments, the flow in the channel is restricted until a threshold pressure (i.e., the high pressure state) in the gate is achieved.

In some embodiments, a fluidic device comprises a channel conduit, a flexible element, and a gate. The channel conduit includes a fluid entrance to the channel conduit and a fluid exit to channel conduit. The channel conduit is bounded by an inner surface that includes a protrusion that protrudes into the channel conduit. The flexible element is inside the channel conduit. The flexible element has at least one edge coupled to the inner surface of the channel conduit on a different side of the inner surface as the protrusion, and the flexible element has an adjustable position. The gate is configured to impart an amount of deformation to the deformable surface in accordance with an applied fluid pressure at the gate. The amount of deformation controls the adjustable position of the flexible element via a cross member that couples the flexible element to the deformable surface. In some embodiments, the fluidic device is part of a haptic device.

In one embodiment, a wearable device is implemented in a system for providing VR, AR, MR, or some combination thereof, experience to a user who wears the device. In more detail, the wearable device provides haptic feedback to the user in response to instructions from a console of the system. The wearable device includes at least one actuator, and a controller. The controller is composed of a plurality of fluidic devices, including at least one fluidic device described herein. In some embodiments, the fluidic devices are coupled together to form one or more composite fluidic devices.

BRIEF DESCRIPTION OF THE FIGURES

FIG. **1**A is a cross section of an example fluidic device functioning as a fluid transistor in a low pressure state, in accordance with an embodiment.

FIG. **1**B is a cross section of the example fluidic device shown in FIG. **1**A in a high pressure state, in accordance with an embodiment.

FIG. **2** is a block diagram of a system environment including a VR system, in accordance with an embodiment.

FIG. **3** is an example haptic glove for interacting with virtual objects, in accordance with an embodiment.

The figures depict embodiments of the present disclosure for purposes of illustration only. One skilled in the art will readily recognize from the following description that alternative embodiments of the structures and methods illustrated herein may be employed without departing from the principles, or benefits touted, of the disclosure described herein.

DETAILED DESCRIPTION

Embodiments of the invention may include or be implemented in conjunction with an artificial reality system. Artificial reality is a form of reality that has been adjusted in some manner before presentation to a user, which may include, e.g., a virtual reality (VR), an augmented reality (AR), a mixed reality (MR), a hybrid reality, or some combination and/or derivatives thereof. Artificial reality content may include completely generated content or generated content combined with captured (e.g., real-world) content. The artificial reality content may include video, audio, haptic feedback, or some combination thereof, and any of which may be presented in a single channel or in multiple channels (such as stereo video that produces a three-dimensional effect to the viewer). Additionally, in some embodiments, artificial reality may also be associated with applications, products, accessories, services, or some combination thereof, that are used to, e.g., create content in an artificial reality and/or are otherwise used in (e.g., perform activities in) an artificial reality. The artificial reality system that provides the artificial reality content may be implemented on various platforms, including a head-mounted display (HMD) connected to a host computer system, a standalone HMD, a mobile device or computing system, or any other hardware platform capable of providing artificial reality content to one or more viewers.

Embodiments of the disclosed invention include fluidic devices used in Virtual Reality (VR), augmented reality (AR) systems, and/or mixed reality (MR) systems. In some embodiments, fluidic devices are devices made of soft materials that use millimeter or smaller channels filled with fluid to transmit information, and the fluidic devices typically implement logic and have control actuators for transmitting information. In one embodiment, the fluidic devices are fluid handling devices that function analogous to electronic devices (e.g., an electrical transistor, an electrical diode, etc.) in electrical systems. Additionally, fluidic devices are composable, meaning that fluidic devices may be coupled together to form a composite fluidic device. In some embodiments, groups of fluidic devices are coupled together to act as controllers for a haptic apparatuses on wearable devices (e.g., haptic gloves) for a VR system.

An embodiment of the fluidic device is discussed in detail below with regard to FIGS. **1**A and **1**B. In general, a state of the fluidic device (e.g., open, closed) controls fluid flow through the channel, and the state is based in part on a gate pressure value.

A flow rate indicates a volume of fluid per unit time flowing through the channel in a fluidic device. An example flow rate is 60 ml/min. The flow rate in a channel of a fluidic device may be affected by, e.g., a pressure of fluid from a corresponding fluid entrance.

An "open" state of a channel refers to a state when the fluid in the channel is flowing from one end to the other end at some open threshold flow rate. In contrast, a "closed" state of the channel refers to the state when the flow of fluid in the channel is less than some closed threshold flow rate, preventing the flow in the channel to flow from one end to the other end. In addition, a "transitionary" state occurs when the channel transitions from an open state to a closed state or from a closed state to an open state.

A "high pressure," a "transitionary" pressure, and a "low pressure" described here depend on the fluidic device structures and pressure of the fluid filling the fluidic device. In general, a "low pressure" is a pressure of the fluid that falls within a low pressure range, a "high pressure" is a pressure of the fluid that falls within a high pressure range, and a "transitionary" pressure is a pressure of the fluid that falls between the low pressure range and the high pressure range. Note, in some embodiments there is a high pressure range and a low pressure range, but not a transitionary range. Moreover, different components of a fluidic device may have different high pressure ranges, different transitionary pressure ranges, and different low pressure ranges. For example, a high pressure range of a gate may be significantly less than a high pressure range of a source.

In one embodiment, a wearable device is implemented in a system for providing VR, AR, MR, or some combination thereof, experience to a user who wears the device. In more detail, the wearable device provides haptic feedback to the user in response to instructions from a console of the system. The wearable device includes at least one actuator, and a controller. The controller is composed of a plurality of fluidic devices as described above. In some embodiments, the fluidic devices are coupled together to form one or more composite fluidic devices. A composite fluidic device is a device formed from a plurality of fluidic devices that are coupled together to form a fluidic circuit, and the fluidic devices are "composable," in that a plurality of fluidic devices may be coupled together to generate larger structures. More details about the "composite fluidic device" can be found in patent application with application number U.S. App. No. 62/449,323 filed on Jan. 23, 2017, which is hereby incorporated by reference in its entirety.

Turning, now to a discussion of an example fluidic device that functions as an fluidic transistor, FIG. **1**A is a cross section of an example fluidic device **100** functioning as a fluidic transistor in a low pressure state, in accordance with an embodiment. The fluidic device **100** includes a channel conduit **105** having a source **110** and a drain **115**, a flexible element **120**, a cross member **125**, and a gate **130**.

The channel conduit **105** is part of the fluidic device **100** and is bounded by an inner surface **135** (**135**A and **135**B collectively referred as **135**) and in the cross section illustrated in FIG. **1**A, one side of the inner surface **135**A and the other side of the inner surface **135**B are shown. In particular, on the side of the inner surface **135**B, there is a protrusion that includes a deformable surface **140** and a surface **145** that are coupled together. The deformable surface **140** can deform according to pressure applied on them. As shown in FIG. **1**A, the deformable surface **140** is positioned adjacent to the gate **130**, and is coupled to the cross member **125** inside the channel conduit **105**, as more fully described below. The channel conduit **105** also includes the source **110** and the drain **115**. The source **110** is also a fluid entrance of the channel conduit **105** and the drain **115** is a fluid exit of the channel conduit, and when the fluidic device **100** is in an open state, the fluid inside the channel conduit flows from the source (fluid entrance) to the drain (fluid exit).

The fluidic device **100** includes a flexible element **120** inside the channel conduit **105**. The flexible element **120** works as a valve to make the channel conduit **105** open or closed. The flexible element **120** is coupled to the side of the inner surface **135**A via a coupling end **150**. The flexible element **120** is coupled to the cross member **125** such that movement of the cross member **125** causes movement of the flexible element **120**. The flexible element **120** may be composed of rigid materials (e.g., metals), semi-rigid materials (plastics), deformable materials (e.g., elastic plastics, silicone rubber, other types of rubber etc.), some other material that allows the flexible element **120** to have an adjustable position, or some combination thereof. In one embodiment, when fluid pressure is greater at the source **110** than at the drain **115** and the gate **130** is in the low pressure state, the flexible element is positioned such that the end **155** is pushed against part of the side of the inner surface **135**B, which closes the channel conduit and inhibits a flow rate within the channel conduit **105** to a threshold flow rate. This places the channel conduit **105** in a closed state.

The cross member **125** works as a medium to transfer force from the deformable surface **140** to the flexible element **120** to cause the end **155** to move. The cross member **125** is positioned inside the channel conduit **105**. As one example, as shown in FIG. **1**A, one end **160** of the cross member **125** is coupled to the flexible element **120**, as described above, and the other end **165** of the cross member is coupled to the inner side of the deformable surface **140**. The cross member **125** can be made of materials such as rigid plastic, metal, or stiff rubber.

The gate **130** is part of the fluidic device **100** that is positioned outside the channel conduit **105** and is adjacent to the deformable surface **140**. In one embodiment, from the cross section of the fluidic device **100** shown in FIG. **1**A, the gate **130** is T-shaped and has one side **170** that is adjacent to the deformable surface **140**. In one embodiment, the gate **130** can be connected to the deformable surface **140** with the side **170** coupled to the deformable surface **140**. The gate **130** has fluid (e.g., liquid or gas) inside it, and the fluid flow inside the gate applies pressure on the side **170** adjacent to the deformable surface **140**. The gate **130** can be in a high pressure state or in a low pressure state. In FIG. **1**A, the gate is in a low pressure state causing the fluidic device **100** to be in a low pressure state, and the channel conduit **105** is in a closed state accordingly.

A low pressure state of the fluidic device **100** indicates that the fluid pressure within the gate **130** is below a certain threshold value (e.g., 5 kPa). While in a low pressure state, the flow rate of fluid within the channel conduit **105** is below a threshold flow rate (e.g., 0.1 mL/s), and in some embodiments, the threshold flow rate may be zero. An example pressure threshold range is 0-100 kPa, and an example threshold flow rate ranges from 0-5 mL/s. In a low pressure state, the gate **130** imparts a small amount of force towards the deformable surface **140** such that the force is not large enough to make the cross member **125** further push the flexible element **120** to open the channel conduit **105**. In the low pressure state, the fluidic device **100** remains a closed state and the fluid inside the channel conduit **105** is inhibited to a threshold flow rate.

FIG. **1**B is a cross section of the example fluidic device **100** shown in FIG. **1**A in a high pressure state, in accordance with an embodiment. In the embodiment of FIG. **1**B, the fluidic device **100** is in a high pressure state. A high pressure state of the fluidic device **100** indicates that the fluid pressure applied on the gate **130** is above a certain threshold and the flow rate of the fluid is above a threshold flow rate. In a high pressure state, with fluid pressure applied on the gate **130**, the gate **130** imparts an amount of deformation on the deformable surface **140**, and the deformable surface **140** deforms accordingly. The amount of deformation of the deformable surface **140** forces the cross member **125** to push the flexible element **120** and forces the flexible element to change its position. Accordingly, as shown in FIG. **1**B, the end **155** of the flexible element **120** is pushed off and apart from the side of the inner surface **135**B, which opens the channel conduit **105** and allows the fluid inside the channel conduit **105** to flow from the source **110** to the drain **115**. When the fluidic device **100** is in a high pressure state, the gate **130** is a high pressure state, and the channel conduit **105** is in an open state.

A transitionary state of the fluidic device **100** is a state between a high pressure state and a low pressure state. As one example, during a transitionary state of the fluidic device **100** from a high pressure state to a low pressure state, the fluid pressure applied on the gate **130** is gradually decreasing until the amount of deformation in the deformable surface **140** cannot push the cross member **125** to maintain the end of the flexible element **120** away from the side of the inner surface **135**B such as to close the channel conduit **105**. As another example, during a transitionary state of the fluidic device **100** from a low pressure state to a high pressure state, the fluid pressure applied on the gate is gradually increasing until the amount of deformation the deformable surface **140** has can push the cross member **125** to make the end of the flexible element **120** away from the side of the inner surface **135**B such as to open the channel conduit **105**.

FIG. **2** is a block diagram of a system **200** including a haptic assembly **205**, in accordance with one embodiment. The system **200** may operate in a VR environment, an augmented reality (AR) environment, a mixed reality (MR) environment, or some combination thereof. The system **200** comprises a head-mounted display (HMD) **210**, an imaging device **215**, and the haptic assembly **205** that are each coupled to a console **220**. While FIG. **2** shows an example system **200** including one HMD **210**, one imaging device **215**, and one haptic assembly **205**, in other embodiments any number of these components may be included in the system **200**. For example, there may be multiple HMDs **210** each having an associated haptic assembly **205** and being monitored by one or more imaging devices **215**, with each HMD **210**, haptic assembly **205**, and imaging device **215** communicating with the console **220**. In alternative configurations, different and/or additional components may be included in the system **200**. Additionally, in some embodiments the system **200** may be modified to include other system environments, such as an AR system environment.

The HMD **210** presents media to a user. Examples of media presented by the HMD **210** include one or more images, video, audio, or some combination thereof. In some embodiments, audio is presented via an external device (e.g., speakers and/or headphones) that receives audio information from the HMD **210**, the console **220**, or both, and presents audio data based on the audio information. The HMD **210** may comprise one or more rigid bodies, which may be rigidly or non-rigidly coupled to each other together. A rigid coupling between rigid bodies causes the coupled rigid bodies to act as a single rigid entity. In contrast, a non-rigid coupling between rigid bodies allows the rigid bodies to move relative to each other. In some embodiments, the HMD **210** may also act as an augmented reality (AR) and/or mixed reality (MR) headset. In these embodiments, the HMD **210** augments views of a physical, real-world environment with computer-generated elements (e.g., images, video, sound, etc.).

The HMD **210** includes an electronic display **225**, an optics block **230**, one or more locators **235**, one or more position sensors **240**, and an inertial measurement unit (IMU) **245**.

The optics block **230** magnifies received light from the electronic display **225**, corrects optical errors associated with the image light, and the corrected image light is presented to a user of the HMD **210**. An optical element may be an aperture, a Fresnel lens, a convex lens, a concave lens, a filter, or any other suitable optical element that affects the image light emitted from the electronic display **225**. Moreover, the optics block **230** may include combinations of different optical elements. In some embodiments, one or more of the optical elements in the optics block **230** may have one or more coatings, such as anti-reflective coatings.

The locators **235** are objects located in specific positions on the HMD **210** relative to one another and relative to a specific reference point on the HMD **210**. A locator **235** may be a light emitting diode (LED), a corner cube reflector, a reflective marker, a type of light source that contrasts with an environment in which the HMD **210** operates, or some combination thereof. In embodiments where the locators **235** are active (i.e., an LED or other type of light emitting device), the locators **235** may emit light in the visible band (~380 nm to 750 nm), in the infrared (IR) band (~750 nm to 1 mm), in the ultraviolet band (10 nm to 380 nm), some other portion of the electromagnetic spectrum, or some combination thereof.

In some embodiments, the locators **235** are located beneath an outer surface of the HMD **210**, which is transparent to the wavelengths of light emitted or reflected by the locators **235** or is thin enough to not substantially attenuate the wavelengths of light emitted or reflected by the locators **235**. Additionally, in some embodiments, the outer surface or other portions of the HMD **210** are opaque in the visible band of wavelengths of light. Thus, the locators **235** may emit light in the IR band under an outer surface that is transparent in the IR band but opaque in the visible band.

The IMU **245** is an electronic device that generates fast calibration data based on measurement signals received from one or more of the position sensors **240**. A position sensor **240** generates one or more measurement signals in response to motion of the HMD **210**. Examples of position sensors **240** include: one or more accelerometers, one or more gyroscopes, one or more magnetometers, another suitable type of sensor that detects motion, a type of sensor used for error correction of the IMU **245**, or some combination thereof. The position sensors **240** may be located external to the IMU **245**, internal to the IMU **245**, or some combination thereof.

Based on the one or more measurement signals from one or more position sensors **240**, the IMU **245** generates fast calibration data indicating an estimated position of the HMD **210** relative to an initial position of the HMD **210**. For example, the position sensors **240** include multiple accelerometers to measure translational motion (forward/back, up/down, left/right) and multiple gyroscopes to measure rotational motion (e.g., pitch, yaw, roll). In some embodiments, the IMU **245** rapidly samples the measurement signals and calculates the estimated position of the HMD **210** from the sampled data. For example, the IMU **245** integrates the measurement signals received from the accelerometers over time to estimate a velocity vector and integrates the velocity vector over time to determine an estimated position of a reference point on the HMD **210**. Alternatively, the IMU **245** provides the sampled measurement signals to the HMD **210**, which determines the fast calibration data. The reference point is a point that may be used to describe the position of the HMD **210**. While the reference point may generally be defined as a point in space; however, in practice the reference point is defined as a point within the HMD **210** (e.g., a center of the IMU **245**).

The IMU **245** receives one or more calibration parameters from the console **220**. As further discussed below, the one or more calibration parameters are used to maintain tracking of the HMD **210**. Based on a received calibration parameter, the IMU **245** may adjust one or more IMU parameters (e.g., sample rate). In some embodiments, certain calibration parameters cause the IMU **245** to update an initial position of the reference point so it corresponds to a next calibrated position of the reference point. Updating the initial position of the reference point as the next calibrated position of the reference point helps reduce accumulated error associated with the determined estimated position. The accumulated error, also referred to as drift error, causes the estimated position of the reference point to "drift" away from the actual position of the reference point over time.

The imaging device **215** generates slow calibration data in accordance with calibration parameters received from the console **220**. Slow calibration data includes one or more images showing observed positions of the locators **235** that are detectable by the imaging device **215**. The imaging device **215** may include one or more cameras, one or more video cameras, any other device capable of capturing images including one or more of the locators **235**, or some combination thereof. Additionally, the imaging device **215** may include one or more filters (e.g., used to increase signal to noise ratio). The imaging device **215** is designed to detect light emitted or reflected from locators **235** in a field of view of the imaging device **215**. In embodiments where the locators **235** include passive elements (e.g., a retroreflector), the imaging device **215** may include a light source that illuminates some or all of the locators **235**, which retro-reflect the light towards the light source in the imaging device **215**. Slow calibration data is communicated from the imaging device **215** to the console **220**, and the imaging device **215** receives one or more calibration parameters from the console **220** to adjust one or more imaging parameters (e.g., focal length, focus, frame rate, ISO, sensor temperature, shutter speed, aperture, etc.).

The haptic assembly **205** is a device that allows a user to send action requests to the console **220**. An action request is a request to perform a particular action. For example, an action request may be to start or end an application or to perform a particular action within the application. The haptic assembly **205** also provides haptic feedback including a perception of contacting a virtual object. In one embodiment, the haptic assembly **205** includes a plurality of composable fluidic devices that form one or more composite fluidic devices. The composite fluidic devices may be used to, e.g., address actuators included in the haptic assembly **205** according to the haptic feedback signal from the console **220**. In one embodiment, as more fully described below in FIG. **3**, the haptic assembly **205** is a haptic glove through which the console **220** enables a user to interact with a virtual object.

In FIG. **2**, the haptic assembly **205** further includes locators **250**, one or more position sensors **255**, and an inertial measurement unit (IMU) **260**. In some embodiments, the locators **250**, one or more position sensors **255**, an inertial measurement unit (IMU) **260** are installed to determine a physical position or movement of the haptic assembly **205**. In addition, the haptic assembly **205** receives, from the console **220**, a haptic feedback signal corresponding to haptic feedback to the user. The haptic assembly **205** provides to the user with the haptic feedback of touching a virtual object in a virtual space, according to the haptic feedback signal. Specifically, the haptic assembly **205** prevents or enables a physical movement of a portion of a user in contact with the virtual object in the virtual space. For example, if a user's finger is in contact with a virtual object (e.g., a virtual wall) in a virtual space, the haptic assembly **205** prevents a physical movement of the user finger to move in a direction through the virtual object in the virtual space. Accordingly, the user can receive a perception of contacting the virtual object.

In one embodiment, the haptic feedback signal indicates a position or a portion of the haptic assembly **205** to be actuated, and an amount of actuation of the position or the portion of the haptic assembly **205** for providing haptic feedback. In this embodiment, the amount of actuation is determined by, e.g., the console **220**, according to a virtual position of the haptic assembly **205** corresponding to a physical position of the haptic assembly **205** and a virtual position of a virtual object in a virtual space. The haptic assembly **205** provides tactile perception of a user touching the virtual object according to the amount of actuation indicated by the haptic feedback signal.

The locators **250** are objects located in specific positions on the haptic assembly **205** relative to one another and relative to a specific reference point of the haptic assembly **205** on the haptic assembly **205**. A locator **250** is substantially similar to a locator **235** except that the locator **250** is part of the haptic assembly **205**. Additionally, in some embodiments, the outer surface or other portions of the haptic assembly **205** are opaque in the visible band of wavelengths of light. Thus, the locators **250** may emit light in the IR band under an outer surface that is transparent in the IR band but opaque in the visible band.

A position sensor **255** generates one or more measurement signals in response to motion of the haptic assembly **205**. The position sensors **255** are substantially similar to the positions sensors **225**, except that the position sensors **255** are part of the haptic assembly **205**. The position sensors **255** may be located external to the IMU **260**, internal to the IMU **260**, or some combination thereof.

Based on the one or more measurement signals from one or more position sensors **255**, the IMU **260** generates fast calibration data of the haptic assembly **340** indicating an estimated position of the haptic assembly **205** relative to an initial position of the haptic assembly **205**. For example, the position sensors **255** include multiple accelerometers to measure translational motion (forward/back, up/down, left/right) and multiple gyroscopes to measure rotational motion (e.g., pitch, yaw, roll) of the haptic assembly **205**. In some embodiments, the IMU **260** rapidly samples the measurement signals and calculates the estimated position of the haptic assembly **205** from the sampled data. For example, the IMU **260** integrates the measurement signals received from the accelerometers over time to estimate a velocity vector and integrates the velocity vector over time to determine an estimated position of a reference point of the haptic assembly **205**. Alternatively, the IMU **260** provides the sampled measurement signals to the console **220**, which determines the fast calibration data of the haptic assembly **205**. The reference point of the haptic assembly **205** is a point that may be used to describe the position of the haptic assembly **205**. While the reference point of the haptic assembly **205** may generally be defined as a point in space; however, in practice the reference point of the haptic assembly **205** is defined as a point within the haptic assembly **205** (e.g., a center of the IMU **260**).

The IMU **260** receives one or more calibration parameters of the haptic assembly **205** from the console **220**. As further discussed below, the one or more calibration parameters of the haptic assembly **205** are used to maintain tracking of the haptic assembly **205**. Based on a received calibration parameter of the haptic assembly **205**, the IMU **260** may adjust one or more IMU parameters (e.g., sample rate). In some embodiments, certain calibration parameters of the haptic assembly **205** cause the IMU **260** to update an initial position of the reference point of the haptic assembly **205** so it corresponds to a next calibrated position of the reference point of the haptic assembly **205**. Updating the initial position of the reference point of the haptic assembly **205** as the next calibrated position of the reference point of the haptic assembly **205** helps reduce accumulated error associated with the determined estimated position.

The console **220** provides media to the HMD **210** for presentation to the user in accordance with information received from one or more of: the imaging device **215**, the VR headset **210**, and the haptic assembly **205**. In the example shown in FIG. **3**, the console **220** includes an application store **265**, a tracking module **270**, and a virtual reality (VR) engine **275**. Some embodiments of the console **220** have different modules than those described in conjunction with FIG. **2**. Similarly, the functions further described below may be distributed among components of the console **220** in a different manner than is described here.

The application store **265** stores one or more applications for execution by the console **220**. An application is a group of instructions, that when executed by a processor, generates content for presentation to the user. Content generated by an application may be in response to inputs received from the user via movement of the HMD **210** or the haptic assembly **205**. Examples of applications include: gaming applications, conferencing applications, video playback application, or other suitable applications.

The tracking module **270** calibrates the VR system **200** using one or more calibration parameters and may adjust one or more calibration parameters to reduce error in determination of the position of the HMD **210**. For example, the tracking module **270** adjusts the focus of the imaging device **215** to obtain a more accurate position for observed locators on the HMD **210**. Moreover, calibration performed by the tracking module **270** also accounts for information received from the IMU **245**. Additionally, if tracking of the HMD **210** is lost (e.g., the imaging device **215** loses line of sight of at least a threshold number of the locators **235**), the tracking module **270** re-calibrates some or all of the system **200**.

The tracking module **270** tracks movements of the HMD **210** using slow calibration information from the imaging device **215**. The tracking module **270** determines positions of a reference point of the HMD **210** using observed locators from the slow calibration information and a model of the HMD **210**. The tracking module **270** also determines positions of a reference point of the HMD **210** using position information from the fast calibration information. Additionally, in some embodiments, the tracking module **270** may use portions of the fast calibration information, the slow calibration information, or some combination thereof, to predict a future location of the HMD **210**. The tracking module **270** provides the estimated or predicted future position of the HMD **210** to the VR engine **275**.

The VR engine **275** executes applications within the system **200** and receives position information, acceleration information, velocity information, predicted future positions, or some combination thereof of the HMD **210** from the tracking module **270**. Based on the received information, the VR engine **275** determines content to provide to the HMD **210** for presentation to the user. For example, if the received information indicates that the user has looked to the left, the VR engine **275** generates content for the HMD **210** that mirrors the user's movement in a virtual environment. Additionally, the VR engine **275** performs an action within an application executing on the console **220** in response to an action request received from the haptic assembly **205** and provides feedback to the user that the action was performed. The provided feedback may be visual or audible feedback via the HMD **210** or haptic feedback via the haptic assembly **205**.

FIG. **3** is an example haptic glove **300** for interacting with virtual objects, in accordance with an embodiment. The haptic glove **300** shown in FIG. **3** includes a glove body **310**, a haptic apparatus **320**, a controller **330**, a signaling path **340**, one or more locators **325**, a position sensor **360** and an IMU **380**. Only signaling path **340**, one haptic apparatus **320**, one position sensor **360** and one IMU **380** are shown in FIG. **3** to simplify the description. In alternative embodiments not shown, the haptic glove **300** can include multiple tubes, position sensors and haptic apparatus that are connected to the controller **330**, for example, for each finger of the haptic glove **300**, a set of haptic apparatus, position sensors and IMUs may be connected to the controller. Likewise, the functions performed by the various entities of the haptic glove **300** may differ in different embodiments. Additionally, the various entities of the haptic glove **300** may be positioned in different places on the glove body **310**. As one example, additional haptic apparatuses **320** and the position sensors **360** are located at different parts of the glove body **310**. As another example, the haptic apparatuses **320** are coupled to or wrap the entire fingers of the glove body **310**. As another example, the controller **330** is coupled to a different portion of the glove body **310** corresponding to, for example a wrist or a palm.

The glove body **310** is an apparatus covering a hand, for example, a garment that is coupled to the position sensor **360**, the haptic apparatus **320**, the controller **330**, and the signaling **340**. In one embodiment, the position sensor **360** is coupled to a corresponding finger of the glove body **310** (e.g., a portion corresponding to a fingertip of the glove body); the haptic apparatus **320** is coupled to a corresponding finger portion (e.g., a portion corresponding to a joint between two phalanges) of the glove body **310**; and the controller **330** is coupled to a portion of the glove body **310** corresponding to a back of a hand (i.e., dorsal side). The signaling path **340** is coupled between the controller **330** and the haptic apparatus **320**. In one embodiment, one or more of these components are placed beneath an outer surface of the glove body **310**, thus are not visible from the outside. Additionally or alternatively, some of these components are placed on an outer surface of the glove body **310**, and are visually detectable.

In one embodiment, the haptic glove **300** may be the haptic assembly **340** shown in FIG. **2** and the locators **325**, the position sensor **360** and the IMU **380** of the haptic glove **300** may be the corresponding locators **250**, position sensors **255** and IMUs **260** of the haptic assembly **205** shown in FIG. **2**. A user's hand movement can be detected and tracked according to fast calibration data from the IMU **380** and/or slow calibration of the locators **325** from the imaging device **335**. Moreover, haptic feedback including a perception of a user contacting a virtual object can be provided to the user by the controller **330**, signaling **340**, and haptic apparatus **320**.

The haptic apparatus **320** provides haptic feedback including a perception of a user touching a virtual object. In one embodiment, the haptic apparatus **320** is actuated according to instructions received from the controller **330**. In one embodiment, the haptic apparatus **320** is coupled to a portion corresponding to a joint between two phalanges of the glove body **310**. In another embodiment, the haptic apparatus **320** covers the entire glove body **310** or are placed on other parts (e.g., an area corresponding to a joint between two different fingers) of the glove body **310**. The haptic apparatus **320** may be, for example, a plurality of actuators.

The controller **330** is a device that provides instructions for the haptic apparatus **320** to perform specific functions. The controller **330** may receive instructions or haptic feedback from the VR console **220** and actuates the haptic apparatus **320** accordingly. The controller **330** includes a plurality of fluidic devices that generate instructions for one or more haptic apparatuses (e.g., actuators). As discussed in detail above, with regard to FIGS. **1A-1B** fluidic devices are composable and may be coupled together to form composite fluidic devices, like, e.g., a decoder. Decoders, for example, can help reduce a number of logical connections within the controller **330** and/or connections to the haptic apparatus **320**. Accordingly, the controller **330** may be composed of a plurality of fluidic devices, including the example device described above with regard to FIGS. **1A-1B**. Similar to the controllers **330**, the signaling path **340** may be a tube or a fluidic device formed from the example fluidic device with reference to FIGS. **1A-1B**. In one embodiment, the example fluidic devices open or close fluidic inputs to actuators, performing logical operations on the instructions passing through the controller **330**.

Additional Configuration Information

The foregoing description of the embodiments of the disclosure have been presented for the purpose of illustration; it is not intended to be exhaustive or to limit the disclosure to the precise forms disclosed. Persons skilled in the relevant art can appreciate that many modifications and variations are possible in light of the above disclosure.

Some portions of this description describe the embodiments of the disclosure in terms of algorithms and symbolic representations of operations on information. These algorithmic descriptions and representations are commonly used by those skilled in the data processing arts to convey the substance of their work effectively to others skilled in the art. These operations, while described functionally, computationally, or logically, are understood to be implemented by computer programs or equivalent electrical circuits, microcode, or the like. Furthermore, it has also proven convenient at times, to refer to these arrangements of operations as modules, without loss of generality. The described operations and their associated modules may be embodied in software, firmware, hardware, or any combinations thereof.

Any of the steps, operations, or processes described herein may be performed or implemented with one or more hardware or software modules, alone or in combination with other devices. In one embodiment, a software module is implemented with a computer program product comprising a computer-readable medium containing computer program code, which can be executed by a computer processor for performing any or all of the steps, operations, or processes described.

Embodiments of the disclosure may also relate to an apparatus for performing the operations herein. This apparatus may be specially constructed for the required purposes, and/or it may comprise a general-purpose computing device selectively activated or reconfigured by a computer program stored in the computer. Such a computer program may be stored in a non-transitory, tangible computer readable storage medium, or any type of media suitable for storing electronic instructions, which may be coupled to a computer system bus. Furthermore, any computing systems referred to in the specification may include a single processor or may be architectures employing multiple processor designs for increased computing capability.

Embodiments of the disclosure may also relate to a product that is produced by a computing process described herein. Such a product may comprise information resulting from a computing process, where the information is stored on a non-transitory, tangible computer readable storage medium and may include any embodiment of a computer program product or other data combination described herein.

Finally, the language used in the specification has been principally selected for readability and instructional purposes, and it may not have been selected to delineate or circumscribe the inventive subject matter. It is therefore intended that the scope of the disclosure be limited not by this detailed description, but rather by any claims that issue on an application based hereon. Accordingly, the disclosure of the embodiments is intended to be illustrative, but not limiting, of the scope of the disclosure, which is set forth in the following claims.

What is claimed is:

1. A fluidic device comprising:

a channel conduit including a fluid entrance to the channel conduit and a fluid exit from the channel conduit, the channel conduit bounded by an inner surface that includes a protrusion that protrudes into the channel conduit;

a flexible element inside the channel conduit, the flexible element having at least one edge coupled to the inner surface of the channel conduit on a different side of the inner surface as the protrusion, the flexible element having an adjustable position; and

a deformable surface that is part of the inner surface of the channel conduit;

a gate configured to impart an amount of deformation to the deformable surface in accordance with an applied fluid pressure at the gate, and the amount of deformation controls the adjustable position of the flexible element via a cross member that couples the flexible element to the deformable surface.

2. The fluidic device of claim **1**, wherein a low pressure state of the gate corresponds to a first flow rate of the fluid in the channel conduit, and a high pressure state of the gate corresponds to a second flow rate of the fluid in the channel conduit, and the second flow rate is greater than the first flow rate.

3. The fluidic device of claim **2**, wherein at the low pressure state of the gate, an end of the flexible element is configured to be in contact with the protrusion to inhibit a flow rate within the channel conduit to the first flow rate.

4. The fluidic device of claim **2**, wherein at the high pressure state of the gate, an end of the flexible element is configured to be apart from the protrusion to allow a fluid to flow within the channel conduit at the second flow rate.

5. The fluidic device of claim **1**, wherein the fluidic device is a component of a wearable device.

6. The fluidic device of claim **1**, wherein the fluidic device is a component of a haptic glove.

7. A fluidic device comprising:

a channel conduit including a fluid entrance to the channel conduit and a fluid exit from the channel conduit, the channel conduit bounded by an inner surface that includes a protrusion that protrudes into the channel conduit;

a flexible element inside the channel conduit, the flexible element having at least one edge coupled to the inner surface of the channel conduit on a different side of the inner surface as the protrusion, the flexible element having an adjustable position;

a cross member with a first end and a second end, the first end coupled to a deformable surface and the deformable surface is part of the inner surface of the channel conduit and the second end is coupled to the flexible element; and

a gate configured to impart an amount of deformation to the deformable surface in accordance with an applied fluid pressure at the gate, and the amount of deformation controls the adjustable position of the flexible element via the cross member.

8. The fluidic device of claim **7**, wherein a low pressure state of the gate corresponds to a first flow rate of the fluid in the channel conduit, and a high pressure state of the gate corresponds to a second flow rate of the fluid in the channel conduit, and the second flow rate is greater than the first flow rate.

9. The fluidic device of claim **8**, wherein at the low pressure state of the gate, an end of the flexible element is configured to be in contact with the protrusion to inhibit a flow rate within the channel conduit to the first flow rate.

10. The fluidic device of claim **8**, wherein at the high pressure state of the gate, an end of the flexible element is configured to be apart from the protrusion to allow a fluid to flow within the channel conduit at the second flow rate.

11. A haptic device comprising:

at least one fluidic device, the fluidic device comprising:

a channel conduit including a fluid entrance to the channel conduit and a fluid exit from the channel conduit, the channel conduit bounded by an inner surface that includes a protrusion that protrudes into the channel conduit,

a flexible element inside the channel conduit, the flexible element having at least one edge coupled to the inner surface of the channel conduit on a different side of the inner surface as the protrusion, the flexible element having an adjustable position,

a cross member with a first end and a second end, the first end coupled to a deformable surface and the deformable surface is part of the inner surface of the channel conduit and the second end is coupled to the flexible element, and

a gate configured to impart an amount of deformation to the deformable surface in accordance with an applied fluid pressure at the gate, and the amount of deformation controls the adjustable position of the flexible element via the cross member.

12. The haptic device of claim **11**, wherein a low pressure state of the gate corresponds to a first flow rate of the fluid in the channel conduit, and a high pressure state of the gate corresponds to a second flow rate of the fluid in the channel conduit, and the second flow rate is greater than the first flow rate.

13. The haptic device of claim **12**, wherein at the low pressure state of the gate, an end of the flexible element is configured to be in contact with the protrusion to inhibit a flow rate within the channel conduit to the first flow rate.

14. The haptic device of claim **12**, wherein at the high pressure state of the gate, an end of the flexible element is configured to be apart from the protrusion to allow a fluid to flow within the channel conduit at the second flow rate.

15. The haptic device of claim **11**, wherein the haptic device is a wearable device.

16. The haptic device of claim **11**, wherein the haptic device is a haptic glove.

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