Fig. 2
DIGITAL HYDRAULIC ACTUATOR

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ABSTRACT OF THE DISCLOSURE

The digital hydraulic actuator disclosed contains a fluid metering feature wherein a so-called "volume piston" is adapted to move back and forth from one end to the other of its accommodating cylinder to transfer fixed and equal amounts of fluid between a fluid supply and a control cylinder containing a movable ram. A solenoid-operated amplitude control valve allows this volume piston to move in the above manner and still feed fluid into one end of the control cylinder to advance the ram in equal incremental steps in a given direction. A solenoid-operated directional control valve determines whether this metered fluid flows into or out of this end of the control cylinder and, consequently, the direction of ram movement.

The present invention relates generally to electromechanical control systems and, more particularly, to apparatus for converting electrical signal information into mechanical displacement.

In numerous electromechanical control systems, it is necessary to convert digital electrical signals into analog movement. One type of apparatus which has been devised for this transformation is the so-called "digital hydraulic actuator." In this hydraulic device, the electrical signals actuate flow valves so that predetermined amounts of fluid corresponding to the information represented by these signals are transferred to and from a control cylinder for positioning an output piston in accordance with the movement desired.

It is accordingly a primary object of the present invention to provide a digital hydraulic actuator wherein a volume piston meters the amount of fluid transferred between the control cylinder and the fluid supply.

Another object of the present invention is to provide a digital hydraulic actuator wherein the fluid entering and leaving the control cylinder is monitored simultaneously.

A still further object of the present invention is to provide a system for translating digital electrical signal information into mechanical movement.

A yet still further object of the present invention is to provide a digital hydraulic actuator having a controlled drift feature.

Other objects, advantages and novel features of the invention will become apparent from the following detailed description of the invention when considered in conjunction with the accompanying drawings wherein:

FIG. 1 illustrates one embodiment of the invention; and

FIG. 2 illustrates an embodiment wherein the fluid entering and leaving the actuating cylinder is metered.

In terms of the above objects of invention are achieved by utilizing as the fluid metering element of the hydraulic system a so-called "volume piston" which is adapted to travel back and forth from one end to the other of its cylinder to transfer fixed and equal amounts of fluid between the fluid supply and the control cylinder. In one modification, a solenoid-operated amplitude control valve which can be set in either of two positions allows this volume piston to move in the bidirectional fashion mentioned above and still feed fluid into one end of the control cylinder to advance the output piston in equal incremental steps in a given direction. To reverse this direction, a second solenoid-operated valve, which likewise can be set in two positions, is employed, and this valve determines whether the metered volume of fluid flows into or out of this end of the control cylinder. The direction of this flow determines the direction of piston advance.

In an alternative embodiment, a pair of volume pistons are utilized, and these pistons meter simultaneously the amount of fluid flowing into one end of the actuating cylinder and the amount of fluid flowing through the other end thereof. The directional valve in this modification determines which end of the cylinder the metered flow enters and leaves.

Referring now to FIG. 1 of the drawings which illustrates an incremental digital actuator, according to one embodiment of the invention, it will be seen that the over-all hydraulic system contains a fluid supply or reservoir 1 to which is coupled a pump 2 for establishing a predetermined high pressure condition in line 3 and the various branch lines, such as 4, 5 and 6 extending therefrom. Included in this system are a pair of solenoid-operated bistable valves 7 and 8. The first of these, valve 7, which controls the amplitude of movement of the output ram 9 accommodated in actuating cylinder 10, includes a spool 11 having lands 12, 13 and 14 mounted thereon. Valve 7 has as its electrical control elements a pair of solenoids 15 and 16 which cooperate with opposite ends of spool 11. In the condition shown in FIG. 1, solenoid 15 has been energized and spool 11 is in its upper position. In this position, line 12 opens a passageway from lines 17, 18 to line 19, while lower land 14 blocks an alternative passageway from lines 17, 20 to line 21. Valve 7, it will be appreciated, remains in the condition shown until solenoid 16 is operated. Then the first path described above is blocked and the second path opened.

Directional valve 8 includes a spool 22 having lands 23, 24 and 25 mounted thereon. This valve, like valve 7, has a pair of solenoids 26 and 27 cooperating with opposite ends of this spool for shifting it between its upper position, the position shown, and its lower position. In its upper position, this valve establishes a fluid passageway between high pressure line 4 and line 17. At the same time, it isolates line 17 from the low pressure or return line 28 leading into reservoir 1. In its lower position, these conditions are reversed. Consequently, a particular setting of directional valve 8 determines whether there is a high pressure condition applied to line 17 and a fluid flow into cylinder 31 or a low pressure condition terminating this line and a fluid flow from this cylinder into reservoir 1.

Volume piston 30 accommodated within cylinder 31 is the fluid metering element of the over-all system. Lines 19 and 21 enter opposite ends of cylinder 31. This piston is adapted to travel from one end to the other of cylinder 31 with each stroke displacing a calibrated volume of fluid. The amount of fluid thus displaced determines the unit of movement of ram 9 in either its forward or backward travel.

Actuating cylinder 10, which houses output ram 9, is connected to amplitude valve 7 by lines 32 and 33. A bidirectional flow of fluid takes place through these lines, depending upon the direction in which ram 9 is being moved. Ram 9 includes a piston head portion 34 whose
diameter corresponds to the inner diameter of cylinder 10 and a shaft portion 35 with reduced diameter to coupled to opposite ends of cylinder 10 by means of lines 6 and 32, ram 9 does not remain stationary but advances to the right because of the greater area of the left-hand face 36 of piston head 34 as compared to its right-hand area. In other words, the pressure applied through line 6 acts only on an annular area of piston head 34 because of the presence of shaft 35 which extends through the right-hand end wall of actuating cylinder 10. In contradistinction, the pressure applied through line 32 acts over the complete face of this piston.

The over-all system also contains an energy storage provision which allows volume piston 30 and control valves 7 and 8 to operate at a high frequency while mass 38 moves smoothly to its proper position. This apparatus includes a pair of auxiliary pistons 40 and 41 accommodated within cylinders 42 and 43, respectively. Each of these has a fluid capacity equal to cylinder 30. Piston 40 has a body portion 44 which fits within line 46. Likewise, piston 41 has a body portion 45 which fits within line 47. The above two lines are coupled to the high pressure lines leading to pump 2. Cylinders 42 and 43 are also connected through lines 49 and 50 and return line 51 to reservoir 1.

In the condition illustrated, the high pressure condition established by pump 2 is acting through lines 3, 4, 17, 18, and 19 into the top of cylinder 31, forcing volume piston 30 to its lower position. When this piston was displaced previously to this position, it discharged a metered amount of fluid out of cylinder 31, and this fluid passed through lines 21, 32, 33 into the left-hand end of actuating cylinder 10, forcing ram 9 an incremental amount to the right, as viewed in this figure. This movement took place despite the high pressure condition acting on face 37 of piston 34 because of the explanation given hereinbefore having to do with the smaller area of the space as compared to face 36. As ram 9 moved to assume the position shown, an appropriate amount of fluid passed out of the right-hand end of cylinder 10 into the high pressure system.

The fluid will remain in the condition shown until either amplitude valve 7 or directional valve 8 is operated by an appropriate electrical signal sent to solenoid 16 or solenoid 26. When solenoid 16 is energized, spool 11 moves downwardly, land 12 blocks the passageway between lines 18 and 19, and land 14 opens the passageway between lines 20 and 21. With directional valve 8 in the condition shown, the high pressure condition now acts through lines 3, 4, 17, 20 and 21 to shift volume piston 30 to the other end of its cylinder. Consequently, a second metered amount of fluid flows out of this cylinder, again through lines 19, 32, and 33, and into actuating cylinder 10, once more displacing ram 9 an incremental distance to the right.

It will be appreciated from what has been described above that if valve 8 remains in the condition shown and amplitude valve 7 is sequentially operated by signals sent alternately to solenoids 15 and 16, volume piston 30 will travel back and forth within its cylinder and ram 9 will be advanced step by step to the right.

To reverse the direction of ram movement, it is only necessary to change the setting of directional valve 8. The position of this valve, it will be seen, determines whether the high pressure condition is applied to line 17 or whether the low pressure condition of reservoir 1 is applied to this line. In the first case, there will be a fluid flow into line 17 and into one or the other end of cylinder 31, depending upon the setting of amplitude valve 7. In the second case, there will be a fluid flow into line 28 and reservoir 1 from one or the other end of cylinder 31, also depending upon the setting of amplitude valve 7. If directional valve 8 is shifted to its lower position by an appropriate electrical signal sent to solenoid 27, then land 24 will isolate line 4 from line 7 and connect line 28 to this same line. The high pressure condition hereforeholding volume piston 30 will now no longer be available for this purpose. Consequently, with amplitude valve 7 in the position shown, fluid will flow from actuating cylinder 10 through lines 32, 33 and 21 into cylinder 31, displacing piston 30 to its upper position. This flow comes about because of the high pressure condition still acting against face 37 of piston 34. Ram 9 will therefore move an incremental distance to the left, which distance, because of the action of volume piston 30, will equal one of the steps it previously took to the right. The fluid discharged from cylinder 31 by the upward stroke of volume piston 30 will pass through lines 19, 18, 17 and 28 back into reservoir 1.

To continue this movement of ram 9 to the left, solenoid 16 of amplitude valve 7 may be operated. This will cause another metered volume of fluid from actuating cylinder 10 to flow out through lines 33, 35 and 19 into cylinder 31, displacing piston 30 to the upper position as shown. A metered amount of fluid will again be discharged back into the reservoir through lines 21, 20, 17 and 28, with the high pressure condition acting on face 37, again bringing about this flow.

From what has been described above, it will be seen that with directional valve 8 in one position and solenoids 15 and 16 sequentially operated, ram 9 will move in equal increments in a first direction and, with directional valve 8 in its other position and these same solenoids again sequentially operated, ram 9 will move in equal increments in an opposite direction. It would also be pointed out that whenever directional valve 8 is shifted from one position to another, ram 9 also moves a single step in the new direction selected.

Auxiliary pistons 40 and 41 are shown in their equilibrium positions, that is, with no energy stored in this portion of the system. If at any time amplitude valve 7 or directional valve 8 is moved to cause fluid to be metered into actuating cylinder 10, a condition which may be considered a positive input to the system, the pressure in chamber 52 communicating with cylinder 43 and line 52 will build up and when it reaches a predetermined level auxiliary piston 41 will move out of line 52 and, it is hoped, cylinder 43 will therefore be able to accept the calibrated fluid volume discharged from cylinder 31. Hence, volume piston 30 will be able to reach its limit of travel within this cylinder and be prepared to accept another command from the electrical control devices even through ram 9 has not attained its ultimate position. The high pressure acting on the rear face of piston 41 will cause this piston subsequently to move back towards its original position, and the fluid discharged from its cylinder 43 will pass into actuating cylinder 10. Thus, ram 9 will move to the right, and this movement will continue until auxiliary piston 41 returns to its equilibrium position. When it is in this position, ram 9 will come to rest at a final position. Auxiliary piston 40 performs in a similar manner when fluid is metered out of actuating cylinder 10. When this discharge takes place from cylinder 10, the pressure in chamber 53 communicating with line 53 drops until it reaches a predetermined level. Then, piston 40 moves off of its stop and a metered amount of fluid is discharged from cylinder 42 into cylinder 31, displacing volume piston 30 to its other position. This piston is therefore again prepared to respond to the appropriate command delivered to it by either amplitude valve 7 or directional valve 8. The fluid discharged out of cylinder 42 is subsequently recovered as ram 9 moves to the left under the action of the high pressure acting on its surface 37. Thus, piston 40 is restored to its initial equilibrium position at the same time ram 9 assumes its final setting.
It will therefore be seen that auxiliary pistons 40 and 41 and their associated cylinders permit energy to be stored in the system so that the setting of the various electrical control devices may be changed prior to the time ram 9 takes up the position required by a previous control signal. This arrangement includes a feature which causes the ram to drift to a center position when no input signals are applied to the various control devices. This arrangement can be used to initialize the system. It can also be used, for example, in a missile guidance control system where two null seeking digital actuators are controlling the pitch of the missile through simulating of the thrust chambers. When the hydraulic power is turned on, these actuators will drift to their neutral positions, thus insuring that the thrust vector acts initially through the center of mass of the missile. After lift-off, the continual drift towards the center will insure that these two actuators perform together and in a compatible manner.

In the system of Fig. 1, the equilibrium condition of ram 9 has a high pressure on the side with the smaller effective area and a medium pressure on the side with the larger effective area. Consequently, there is a tendency for the ram to drift to the right as fluid leaks from the right-hand end to the left-hand end of cylinder 10 through the external leakage path 55. However, if the ram is, for example, in the right-hand half of the cylinder, there is an additional leakage out through drift path 56, located in the middle of cylinder 10 and connected by a line, not shown, to the reservoir 1. Thus, there is a tendency for the ram to drift to the left. However, if this drift to the left is made larger than the drift to the right, the direction of net drift of ram 9 will always be toward the center of actuating cylinder 10 and the objectives mentioned above will be achieved. Leakage paths 55 and 56 can be foreseen in many ways. One simple method is to force a screw into the line so that the fluid flow can only take place around the finite helical path provided by the screw threads. A restriction 57 may also be placed in line 6 at a point adjacent to its connection to actuating cylinder 10 to provide damping of output ram 9.

Fig. 2 illustrates an alternative modification of the invention in which the fluid entering one end of actuating cylinder 69 and that leaving the other end of this cylinder are metered simultaneously by a pair of volume pistons 61 and 62 accommodated within cylinders 63 and 64, respectively. These cylinders have the same fluid capacity so that both pistons displace equal fluid volumes. In this system the pressure acting on one side of piston 90 of output ram 65 is raised to the high pressure level while that on the other side is lowered concurrently to the return pressure. For a given size actuating cylinder a greater force is therefore available for moving the load 112 connected to the ram.

In this alternative system, amplitude valve 66 has a spool 67 on which are mounted lands 68, 69, 70, 71 and 72. Solenoids 73 and 74, when selectively energized, shift this spool between an upper position, the one shown, and a lower position. Directional valve 75 has a spool 76 which is mounted on which are mounted lands 77, 78 and 79. Solenoids 80 and 81, when selectively energized, shift this spool between a lower position, the position shown, and an upper position. This system also includes an arrangement for dampening the movement of ram 65. This apparatus, generally represented by reference character 82, consists of three interconnected pistons 83, 84 and 85. Each cylinder contains a free moving piston, such as 85, 87 and 88, and these pistons are separated by cylindrical rods 89 and 91. The three pistons are not connected to these rods but rather these rods merely contact their faces. Cylinders 83 and 85 are connected to the high pressure pump 95 by means of lines 113 and 114. Since equal high pressures are applied to the free ends of pistons 86 and 87, these pistons normally occupy the positions shown, holding piston 87 in the center of its cylinder 84.

The operation of the damping device is as follows: If a metered amount of fluid, for example, is discharged from cylinder 63 as a result of a downward stroke of volume piston 61, this fluid will flow via lines 99 and 109 into the right-hand side of actuating piston 87, rod 89 and piston 86 to the left against the restraining action of the high pressure backing up piston 86. Thereafter, this back pressure will be effective to restore these elements to their original position and the previously transferred fluid will pass out of the right-hand side of actuating cylinder 84 through line 101 into the right-hand side of actuating cylinder 60, forcing piston 90 of ram 65 to the left to assume its proper position. Thus, the impact initially accompanying the fluid transfer brought about by a stroke of the volume piston will be taken up by an appropriate response of the damping apparatus and not the ram.

Piston 90 of ram 65, unlike its counterpart in Fig. 1, has faces of equal area because of the presence of shafts 110 and 111 which extend through opposite end walls of actuating cylinder 60. The load represented by 112 may be connected to one of these shafts, such as 110. It is believed that a detailed discussion of the operation of the complete system of Fig. 2 is unnecessary in view of the analysis of Fig. 1 given hereinbefore. However, it would be pointed out that in the condition illustrated, the high pressure condition produced by pump 95 is acting through lines 96, 97 and 98, forcing volume piston 61 to the position shown. When this piston previously moved to this position, a metered amount of fluid passed out of its cylinder 63 through lines 99 and 106, first into the right-hand side of cylinder 84 of the dampening apparatus and then into the right-hand side of actuating cylinder 60. Ram 65, consequently, moved an incremental distance to the left to allow this fluid to be accepted by this cylinder.

The fluid discharged from the left-hand side of actuating cylinder 60 in response to this movement passed into cylinder 64 via lines 102, 103 and 104, forcing volume piston 62 to the position shown. The fluid discharged from this cylinder by this stroke of volume piston 62 passed into reservoir 115 via lines 105, 106 and 107.

During this previous movement of ram 65, it should be appreciated, a high pressure condition acted on the right side of piston 90 and a low pressure exerted on the left side of this piston. Consequently, as mentioned hereinbefore, the net force available for displacing this piston was greater than that experienced by ram 9 in Fig. 1. Hence, for the same size actuating cylinder, the arrangement of Fig. 2 can control a greater load.

If amplitude valve 66 is now shifted to its lower position by an appropriate signal sent to solenoid 74, the high pressure condition will act through lines 96, 97, 117 and 99 to displace volume piston 61 to its upper position, a metered amount of fluid will again enter the right-hand end of actuating cylinder 60 and ram 65 will once more move to the right a calibrated amount. The fluid discharge from the left-hand end of cylinder 60 will be metered as it passes into cylinder 64 through lines 102, 103 and 105, volume piston 62 will shift to its other position and an appropriate amount of fluid will flow back into the reservoir through lines 104, 116 and 107. It will thus be seen that amplitude 65 in this modification performs like amplitude valve 7 of Fig. 1.

Likewise, if directional valve 75 is shifted to its upper position by an appropriate signal to solenoid 80 and with amplitude valve 66 left in the position shown and the various volume pistons in the positions shown, the high pressure condition will act through lines 96, 106 and 105 to force volume piston 62 to its other position and a metered amount of fluid will pass out of its cylinder 64 through lines 104, 103 into first the left-hand end of cylinder 84 of the damping apparatus and then out therefrom and through lines 105 into the left-hand end of actuating cylinder 60. Consequently, ram 65 will
be moved an incremental amount to the right. The fluid discharge from the right-hand end of actuating cylinder 60 to accommodate this movement will be metered as it flows through lines 161, 100 and 99 into cylinder 33. When this flow occurs, volume piston 61 will be moved to its other position and an appropriate amount of fluid will pass from this cylinder through lines 98, 97 and 118 back into reservoir 115.

It will thus be seen that ram 65 in this embodiment can be selectively controlled to the same extent as ram 9 in FIG. 1. In practice, the computer associated with these systems will determine whether a positive increment is needed, whether a negative increment is needed, or whether the present position of the ram is proper. It will then generate an appropriate code to the various solenoids associated with the amplitude and directional valves to bring about the required movement.

Obviously many modifications and variations of the present invention are possible in the light of the above teachings. It is therefore to be understood that within the scope of the appended claims the invention may be practiced otherwise than as specifically described.

What is claimed is:

1. A digital hydraulic actuator comprising, in combination,
a first enclosed cylinder having a fluid opening at each end thereof;
a free moving piston accommodated within said cylinder and adapted to travel from one end to the other of said cylinder thereby to discharge through one or the other of said fluid openings a metered amount of fluid;
an enclosed actuating cylinder having a fluid opening at each end thereof;
a ram accommodated within said actuating cylinder, said ram comprising a cylindrical piston head and a shaft portion of reduced diameter which extends through one end wall of said actuating cylinder for attachment to a load device;
a high pressure fluid source;
said high pressure fluid source being applied to a portion of the back face of said piston head so as to bias said ram in one direction;
a low pressure fluid source;
means for controlling the flow of fluid between said sources, said first cylinder and said actuating cylinder such that whenever high pressure source is connected to one opening of said first cylinder, a metered amount of fluid is discharged to the other opening of that cylinder into one opening of said actuating cylinder to move said ram an incremental distance in the opposite direction, and whenever said low pressure source is connected to one opening of said first cylinder a metered amount of fluid is discharged out of said opening of said actuating cylinder into the other opening of said first cylinder and said ram is moved the same incremental distance in said direction by said high pressure fluid source applied to a portion of the back face of said piston head;
and energy storage means cooperating with said first enclosed cylinder and said actuating cylinder for initially accepting the fluid discharge from said first enclosed cylinder and then transferring it to said actuating cylinder and for initially accepting the fluid discharge from said actuating cylinder and then transferring it to said first enclosed cylinder whereby the free moving piston can start to travel from one end to the other end of said first enclosed cylinder before said ram reaches its final setting.

2. In an arrangement as defined in claim 1 wherein said means for controlling the flow of fluid between said sources, said first cylinder and said actuating cylinder includes:
a bistable directional valve and a bistable actuating cylinder,
said bistable directional valve in one of its positions connecting said high pressure source and in the other of its positions connecting said low pressure source to one or the other of said first cylinder, depending upon whether said amplitude valve is in one or the other of said positions.

3. In an arrangement as defined in claim 2 wherein said amplitude valve connects the high pressure source or the low pressure source depending upon the position of said bistable directional valve to one or the other of said openings of said first enclosed cylinder.

4. In a digital hydraulic actuator comprising, in combination,
a first enclosed cylinder having a fluid opening at each end thereof;
a free moving piston accommodated within said cylinder and adapted to travel from one end to the other of said cylinder, thereby to discharge through one or the other of said fluid openings a metered amount of fluid;
an enclosed actuating cylinder having a fluid opening in each end thereof;
a ram accommodated within said actuating cylinder, said ram having a cylindrical piston head and a shaft portion of smaller diameter which extends through one end wall of said actuating cylinder for attachment to a suitable load device;
a reservoir having fluid stored therein;
a pump having an input and an output side with said input side connected to said reservoir;
a bistable directional valve having first, second and third fluid openings,
said valve in one of its positions permitting a fluid flow only between said first and third openings and in its other position permitting a fluid flow only between said first and second openings;
a bistable amplitude valve having first, second, third, fourth and fifth fluid openings,
said amplitude valve in one of its positions permitting a fluid flow only between said first and second openings and between said third and fourth openings and in its other position permitting a fluid flow only between said second and third openings and said fourth and fifth openings;
conduit means connecting the output of said pump to both the third opening of said directional valve and the opening in said actuating cylinder which is at that end of said actuating cylinder through which said shaft extends, said reservoir to the first opening of said directional valve, the second opening of said directional valve to both the first and fifth openings of said amplitude valve, the second opening of said amplitude valve to one of the openings of said first enclosed cylinder, the fourth opening of said amplitude valve to the other opening of said first enclosed cylinder and the third opening of said amplitude valve to the other opening of said actuating cylinder;
and energy storage means connected between the conduit means that connects said third opening of said amplitude valve to the other opening of said actuating cylinder and the conduit means which connects the third opening of said directional valve to the opening of said actuating cylinder which is at that end thereof through which said shaft extends for initially accepting the fluid discharge from said enclosed cylinder and then transferring it to said actuating cylinder and for initially accepting the fluid discharge from said actuating cylinder and then trans-
ferring it to said first enclosed cylinder whereby said free moving piston can start to travel from one end to the other end of said first enclosed cylinder before said ram reaches its final setting.

5. In an arrangement as defined in claim 4, wherein an external fluid passageway of restricted area interconnects the opposite ends of said actuating cylinder, and wherein said actuating cylinder has a third fluid opening at a point midway between its end walls and a fluid passageway of restricted area connected between said reservoir and said third fluid opening.

6. A digital hydraulic actuator comprising, in combination,
a first enclosed cylinder having a fluid opening at each end thereof;
a second enclosed cylinder of the same size as said first cylinder having a fluid opening at each end thereof;
each cylinder having a free moving piston accommodated therein which is adapted to travel from one end to the other end of the cylinder thereby to discharge through one or the other of said fluid openings a metered amount of fluid;
an enclosed actuating cylinder having a fluid opening at each end thereof;
a ram accommodated within said actuating cylinder, said ram comprising a cylindrical piston having shaft portions of smaller diameter secured to opposite sides of said piston which extend through opposite end walls of said actuating cylinder;
a low pressure fluid source;
a high pressure fluid source;

and means for controlling the flow of fluid between said sources, said first and second cylinders and said actuating cylinder, such that whenever said high pressure source is connected to one opening of said first cylinder a metered amount of fluid is discharged through the other opening of that cylinder into one opening of said actuating cylinder and a metered amount of fluid is discharged from the other opening of said actuating cylinder into one opening of said second cylinder and said ram moves an incremental distance in one direction, and such that whenever said high pressure source is connected to one opening of said second cylinder a metered amount of fluid is discharged from the other opening of that cylinder into one opening of said actuating cylinder and a metered amount of fluid is discharged from the other opening in said actuating cylinder into one opening of said first cylinder and said ram moves an incremental distance in an opposite direction.

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