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Print Figure: 3

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(NASA-Case-MS-22021-1) APPARATUS  
AND METHOD FOR PRODUCING AN  
ARTIFICIAL GRAVITATIONAL FIELD  
Patent Application (NASA) 24 p

N94-15935

Unclass

## APPARATUS AND METHOD FOR PRODUCING AN ARTIFICIAL GRAVITATIONAL FIELD

The concept of rotating a mass about a spin axis to produce artificial gravity is well known. Typically, however, it has been necessary to stop such rotation in order to make changes in translational velocity ( $\Delta V$ ) if the thrust is applied offset from the spin axis. The rotation is then recreated after  $\Delta V$  changes. Both stopping and resuming spin wastes energy.

The present invention provides means for balancing the off-center thrust to prevent unwanted rotation of the spacecraft while preserving the rotation which produces the artificial gravity field. To balance the unwanted rotational effects of the drive force which is offset with respect to the spin axis, a mass displacement means shifts part of the mass of the rotating spaceship. The shifted mass, which is also rotating, induces an opposing moment to the moment created by offset drive force. This induced opposing moment may be calibrated to exactly counterbalance the moment created by offset drive force. In a preferred embodiment, the mass displacement means shifts the mass of the crew cabin, the mass of the drive engine, or both. The mass displacement means may vary the amount of mass movement to account for variations in drive force. If the drive force is reduced to zero, the mass displacement means returns the mass to an original position.

Novelty is believed to reside in the apparatus and method for counteracting undesirable rotation caused by offset thrust without altering artificial gravity rotation.

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**APPARATUS AND METHOD FOR PRODUCING AN ARTIFICIAL  
GRAVITATIONAL FIELD**

ORIGIN OF THE INVENTION

5           The invention described herein was made by an employee of the United States Government and may be manufactured and used by or for the Government of the United States of America for governmental purposes without payment of any royalties thereon or therefor.

Technical Field

10           The present invention relates to apparatus and method for creating a centrifugal force to serve as an artificial gravitational field in a rotating spacecraft. More particularly, the present apparatus is directed to counteracting unwanted rotations induced by engine thrust offset from the center of mass of the rotating spacecraft while maintaining the desired rotation that produces an artificial gravitational field.

15           Background Art

          Long space voyages in diminished gravity or weightlessness conditions are often detrimental to the health of human space travelers. The relative ease the heart experiences by pumping blood in a weightless environment produces a cardiovascular deconditioning effect. Also, without a gravitational force, body fluids migrate upwards in the body to create  
20 congested areas. Thus, for long space voyages, such as an expedition to Mars, some means for generating an artificial gravitational force is desirable.

Prior inventors have recognized some of these problems. U.S. Patent No. 3,675,879 to H.B. Fuchs discloses a means for generating an artificial gravitational force including an electrostatic generator at the underside of a floor in a space vehicle. The electrostatic energy attracts the footwear, clothing, and the implements used by the astronauts to the topside of the floor in simulation of gravity. However, this method may not attract all body components with the same force.

U.S. Patent No. 5,058,834 to C. H. Hubert discloses an apparatus for adjusting the balance of a spin-balanced spacecraft. The apparatus moves a liquid between or among containers spaced about the spin axis. The transfer is accomplished by controllable heaters associated with each container for heating that container from which liquid is to be transferred to increase fluid pressure. This method does not describe how unwanted rotations induced by engine thrusting offset from the spin axis may be counter-balanced.

U.S. Patent No. 4,688,746 discloses an apparatus for despinning a satellite whereby one or more spinning flywheels are adapted to despin or partially despin a rotating mass, such as a satellite, and to convert the rotational energy into heat or electrical energy. This disclosure does not teach how to balance unwanted rotations induced by engine thrusting offset from the spin axis while maintaining a desired rotation that produces an artificial gravitational field.

U.S. Patent No. 5,129,600 to M.E. Polites discloses an apparatus using one or more rotating unbalanced mass devices for selectively generating circular, line, or raster scan patterns with gimbaled experiments. The rotating unbalanced mass makes use of a mass associated with a drive shaft, with the mass having a center of gravity that is displaced from the drive shaft rotation axis. The resulting centrifugal force of the rotating unbalanced mass is used to generate desired reaction forces on the experiment to create a desired scan pattern for the experiment line of sight. This disclosure does not teach how to balance unwanted rotations induced by forces applied offset from the spin axis while maintaining a desired rotation.

U.S. Patent No. 5,130,931 to Paluszek et al. discloses a spacecraft attitude and/or velocity control system including a controller which responds to at least attitude errors to produce commanded signals representing a force vector and torque vector. These vectors each have three orthogonal components, which represent the forces and torques that are to be generated by the thrusters. This method requires additional thrusters with additional corresponding fuel requirements. This method may also require location of heat producing or particle producing engines near the crew cabin.

One method for producing an artificial gravitational field, known to those skilled in the art, involves rotation of a spacecraft to simulate the gravitational force. For this application, the spacecraft crew cabin is located at the fore portion of the spacecraft. A main rocket engine is positioned at the aft portion of the space ship. In the operation of this method, the spacecraft is first directed in the correct direction for the long voyage at the desired velocity. Then, the space ship is made to spin end over end to produce an artificial gravity. The spin axis is transverse to the direction of travel. The rocket engine acts as a counter balance for the weight of the crew cabin. The engine, which may be a nuclear or solar electric engine, is kept a good distance from the crew cabin to generate sufficient artificial gravitational force, and to decrease radiation exchange between the crew cabin and engine. However, the problem of this method lies in the need to despin and respin each time a course correction is necessary. The despinning and respinning process requires excessive fuel expenditures.

Another prior art method for producing an artificial gravitational force involves rotating the spacecraft from port to starboard. The crew cabin and a counterweight are cantilevered on opposite sides of the spacecraft fuselage or center truss of the spacecraft. In this method, the spin axis points in the same direction or parallel to the direction of flight. With this method, it is not necessary to despin and respin with the spacecraft each time course corrections are made. The spacecraft, including the main engine or engines, can be reoriented to make course corrections using reaction-control rockets that are typically



that is used as an artificial gravitational field. The drive engine acts as the counterweight for the crew cabin, in which the artificial gravity field is induced, as the engine also rotates about the desired spin axis. The centrifugal forces induced by rotation in the crew cabin and engine, respectively, oppose each other. The spacecraft has a center of mass through which  
5 the desired spin axis extends.

To balance the effects of the drive force from the drive engine that is offset with respect to the spin axis, a mass displacement means shifts part of the mass of the rotating spaceship. The shifted mass, which is also rotating, induces an opposing moment to the moment created by offset drive force. This induced opposing moment may be calibrated to  
10 exactly counterbalance the moment created by offset drive force.

In a preferred embodiment, the mass displacement means shifts the mass of the crew cabin, the mass of the drive engine, or both. Thus, there is little or no deadweight, i.e., otherwise unusable weight. The mass displacement means may vary the amount of mass movement to account for variations in drive force. If the drive force is reduced to zero, the  
15 mass displacement means returns the mass to an original position.

An objective of the present invention is to generate a centrifugal force to provide an artificial gravitational field within the crew cabin of a spacecraft by rotating the spacecraft.

Another objective of the present invention is to eliminate deadweight associated with a counterweight in a rotating spacecraft.

20 A feature of the present invention is a mass displacement means to balance the effects of a drive engine that produces a drive force offset from the spin axis of the spacecraft.

An additional feature of the present invention is a mass displacement means that displaces the mass of otherwise functional components of the spacecraft to balance the effects of a drive engine that produces a drive force offset from the spin axis of the  
25 spacecraft.

An advantage of the present invention is the capability of using the drive engine of the spacecraft as a counterweight for the crew cabin.

Another advantage of the present invention is the option to locate the crew cabin and particle producing engine a maximum distance from each other.

### BRIEF DESCRIPTION OF THE DRAWINGS

5

Other features and intended advantages of the present invention will be readily apparent by the references to the following detailed description in connection with the accompanying drawings, wherein:

Fig. 1 is a diagrammatic representation of a prior art spacecraft operable for  
10 generating an artificial gravitational field;

Fig. 2 is a diagrammatic representation of another prior art spacecraft operable for generating an artificial gravitational field;

Fig. 3 is a diagrammatic representation of a spacecraft having desirable features for generating an artificial gravitational field but which is otherwise impractical due to  
15 undesirable rotations that arise from a moment created when the drive force is generated offset from the center of mass of the spacecraft;

Fig. 4 is a schematic representation of the spacecraft of Fig.3 but includes means for counterbalancing the undesirable rotations in accord with the present invention; and

Fig. 5 is a schematic representation of an alternative embodiment of a spacecraft in  
20 accord with the present invention.

Fig. 6 is a schematic representation of another embodiment of a spacecraft in accord with the present invention.

While the invention will be described in connection with the presently preferred embodiments, it will be understood that it is not intended to limit the invention to these  
25 embodiments. On the contrary, it is intended to cover all alternatives, modifications, and equivalents as may be included in the spirit of the invention.

## DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

The present invention relates to methods and apparatus for producing an artificial gravity environment within a crew cabin of a spacecraft. The spacecraft rotates to induce a centrifugal force within the crew cabin that serves as an artificial gravitational field. More particularly, the present apparatus includes a drive engine that propels the rotating spacecraft in a desired direction typically parallel to the rotation or spin axis. However, the drive engine produces a drive force offset from the spin axis thus potentially inducing undesirable rotation of the spacecraft.

In general, rotation in a particular rotational direction about the center of gravity of a spacecraft may be described by an angular velocity vector. However, for purposes of this specification, rotational direction is more simply as described in terms of a spin axis that extends through the center of mass of the spacecraft.

That is, the rotational direction delineates a particular spin axis where all elements of the spacecraft rotate around the spin axis. The spin axis is not a point, such as the center of mass of the spacecraft around which the spacecraft rotates, but is an axis about which the spacecraft rotates. The spin axis, therefore, is also described by a plane or set of planes orthogonal to the spin axis in which each particle comprising the spacecraft rotates. The rotational motion of each particle about the spin axis is also orthogonal to the spin axis.

As used in this specification, the center of mass for many particles distributed in space and comprising a spacecraft is defined as follows:

$$\overline{r_{cm}} = \frac{1}{M} \sum \overline{r_i} m_i$$

where

$\overline{r_{cm}}$  is a position vector for the center of mass of the spacecraft,

$M$  is the total mass of the spacecraft,  
 $m_i$  is the mass of each particle  $n$ , and  
 $\overline{r}_i$  is the position vector for each particle  $n$ .

A feature of the present invention is a drive engine offset from the center of mass of  
5 the spacecraft. Such a drive force with a line of action not intersecting the center of mass  
creates a moment. A moment may be described as a product of a force and the perpendicular  
distance of the force from a point of interest, such as the center of mass of a spacecraft. A  
moment, when acting on a body such as a spacecraft, will have a tendency to rotate the  
spacecraft. Depending on rules of construction for two dimensional action, clockwise  
10 moments are usually considered positive, and counterclockwise moments are negative. As  
discussed herein moments may act in three dimensions but if they are opposite in direction  
and magnitude they counterbalance each other so there is no tendency for rotation of the  
spacecraft. A moment on a spacecraft may be produced by firing a rocket offset from the  
center of mass of the spacecraft. A moment on a rotating spacecraft may also be produced  
15 when the combined masses of the spacecraft can not be all effectively centered in a single  
plane perpendicular to the rotation vector or spin axis. Thus, moments that arise from two  
sources may be used to balance each other out as discussed in more detail hereinafter.

Fig. 1 shows prior art spacecraft 10a which produces a gravitational field by rotation  
of spacecraft 10a. Spacecraft 10a includes a crew cabin 14 and engine 16 connected by truss  
20 18. Engine 16 provides a drive force to accelerate spacecraft 10a in the direction of arrow 12  
during course maneuvers. Rockets or jets 20 and 22 produce a thrust force to rotate  
spacecraft 10a in a rotational direction having spin axis 24 when the spacecraft is not  
accelerating. Spin axis 24 extends through center of gravity 26 of spacecraft 10a.

The rotation creates a centrifugal force in crew cabin 14 that opposes a centrifugal  
25 force acting on engine 16. The centrifugal force serves as the artificial gravitational field.  
The magnitude of the centrifugal force is partly determined by the separation along truss 18

between engine 16 and spin axis 24 or crew cabin 14 and spin axis 24. Spacecraft 10a provides a large separation along truss 18 between engine 16 and crew cabin 14. The large separation also protects any space travelers in crew cabin 14 from engine 16 which may be radioactive or produce particles deleterious to the health of such space travelers, or provide a poor thermal environment for other spacecraft systems. However, a problem with this spacecraft is that to have a fixed, controlled engine orientation to drive course maneuvers requires despinning (and subsequent respinning) each time, which may use considerable fuel. Thus, this method of producing an artificial gravity is inefficient for fuel consumption.

Referring to Fig. 2 there is indicated a method for producing an artificial gravity that does not require despin and respin when correcting course. This method is also known to those skilled in the art. Spacecraft 10b accelerates in the direction of arrow 28 propelled by drive engine 30. Crew cabin 36 rotates around spin axis 38 to produce an artificial gravitational field within the crew cabin 36. Counterweight 40 is necessary to delineate the spin axis 38 around which both crew cabin 36 and counterweight 40 rotate. Rockets 32 and 34 initiate and control rotation of crew cabin 36 and counterweight 40 around spin axis 38, which is typically parallel to the direction of acceleration during course corrections. These rockets thus control the magnitude of the centrifugal force which is used as an artificial gravitational field. Arms 42 and 44 secure and position crew cabin 36 and counterweight 40, respectively, to main central truss 46.

The direction of acceleration and travel of spacecraft 10b can be readily altered. A gimbaled drive engine nozzle, or reaction-control rockets--similar to 32 or 34, which are typically disposed about a spacecraft--are used for this purpose. The thrust of drive engine 30 in a different direction effectively alters the direction of acceleration and travel of the spacecraft.

A major problem associated with spacecraft 10b lies in counterweight 40 which is typically deadweight, i.e., otherwise unusable weight. Use of a deadweight for counterweight 40 requires considerable energy for placement of the deadweight in space. If

counterweight 40 has no other purpose than to act as a counterweight, the energy required to place counterweight 40 in space is somewhat wasted.

Plausibly, a fuel tank could be used as counterweight 40. However, the length of the arm 42 of the counterweight 40, which in this case includes the fuel, requires adjustment to compensate for expended fuel. Alternatively, the length of arm 44 may be altered as the fuel is expended. Fuel could also be pumped from one position to another. However, at some point in time, there may be no additional fuel to pump for compensation purposes. Thus, counterweight 40, comprising either a deadweight or fuel as part of the counterweight, poses problems for spacecraft 10b.

Spacecraft 10c, shown in Fig. 3, accelerates in the direction indicated by arrow 50. Spacecraft 10c uses engine 52 as a counterweight for crew cabin 54. Rockets 56 and 58 induce rotation of crew cabin 54 and drive engine 52 around spin axis 60. Spin axis 60 is parallel to the intended direction of acceleration arrow 50. Spacecraft 10c, like spacecraft 10b, does not require despin and respin for course corrections. Spacecraft 10c does not include so-called deadweight as does spacecraft 10b since drive engine 52 is used as a counterweight for crew cabin 54. Drive engine 52 supplies a drive force that propels spacecraft 10c in the direction of arrow 50. Drive engine 52 and crew cabin 54 may be a considerable distance apart to protect space travelers from the engine's environment.

However, the drive force from engine 52 creates an additional moment acting on spacecraft 10c that tends to cause an unwanted rotation around center of mass 66. This unwanted rotation, for the instantaneous position of rotating spacecraft 10c, is shown by arrows 68 and 70. The unwanted moment arises because engine 52 produces force with a line of action offset from center of mass 66. Thus spacecraft 10c has significant orientation problems created by the unwanted moment which make control of orientation of spacecraft 10c difficult. This is true even though spacecraft 10c has many advantages over the prior art i.e. unwasted use of the engine as a counterweight for rotation and a significant distance between the engine and the crew cabin.

The spacecraft of the present invention includes the advantages of the general configuration of spacecraft 10c shown in Fig. 3 while overcoming the orientation control problems caused by drive engine forces offset from center of mass 66. The present invention may also be used with other similar spacecraft configurations as discussed hereinafter. The present invention includes means to compensate for the unwanted moment and rotation produced by the offset drive force.

A schematic illustration of spacecraft 10d in accord with the present invention is shown in Fig. 4. Crew module 80 and drive engine 82 rotate in a specific rotational direction about a spin axis 84 at specific distances  $r_c$  and  $r_e$  (respectively) from that spin axis to create an artificial gravitational force within crew module 80. Thus, crew cabin 80 and drive engine 82 act as counterweights with respect to each other. The crew cabin 80 and engine 82 experience opposed centrifugal forces due to the rotation of spacecraft 10d about spin axis 84. As in other spacecraft designs shown in Fig. 1 - 3, the centrifugal force acting on crew cabin 80 provides an artificial gravitational force for space travelers inside the crew cabin.

The direction of linear acceleration of spacecraft 10d is indicated by arrow 86 and must be parallel to spin axis 84. Thus, the centrifugal forces perceived by rotation around spin axis 84 are transverse to and at right angles to the direction of acceleration 86 during course maneuvers. Though when not accelerating it is not required and may not be desired that the spin axis 84 and direction of travel of spacecraft 10d be parallel.

Similarly to spacecraft 10c, engine 82 creates a moment that may rotate spacecraft 10d in a rotation having a different rotational direction and spin axis than the desired rotation with spin axis 84. The moment is created by a drive force from engine 82 that is typically parallel to the desired spin axis 84.

However, spacecraft 10d provides means for eliminating the effects of the moment created by the drive force from engine 82. The compensation means, in this embodiment of the invention, operates by translating or displacing the mass of engine 82 in the direction of thrust typically parallel to spin axis 84. Rail 85 and wheels 88 are shown for illustrative

purposes as a means for translating engine 82; other means could also be used. The movement forward of engine 82 any distance  $s$  parallel to spin axis 84 acts to shift the center of mass of spacecraft 10d forward along spin axis 84 by a distance  $dx$  which is less than  $s$ . Most importantly, the translation of engine 82 by distance  $s$  moves the line of action of the centrifugal force acting on that engine forward by that distance  $s$ .

The new position at  $s$  of the centrifugal force on engine 82 at a point forward of the new position at  $dx$  of the center of mass induces a moment that is opposite in direction to the moment created by the drive force of engine 82. The centrifugal force of the engine  $m_e * r_e * \omega^2$  is acting at a moment arm  $s - dx$  that is the difference between the engine center of mass and the vehicle center of mass. Essentially, a rotating mass, i.e., drive engine 82, is shifted the distance  $s - dx$  out of the plane in which the effective rotating mass of the spacecraft is located. This condition induces a moment. By adjusting the translation distance  $s$ , the magnitude of induced moment can be regulated to cancel out the moment (force  $F$  at moment arm  $r_e$ ) created by the off center thrust. Thus, the unwanted rotation can be eliminated by relatively simple mechanical means that expend little or no fuel.

It is possible to solve mathematically for the length  $s$  required to move engine 82 for this purpose. This may be accomplished by summing up the moments and centrifugal forces acting on spacecraft 10d and solving for  $s$  to obtain:

$$s = F / (\omega^2 * m_e)$$

where the difference in mass distributions of the truss sections on either side of the axis is negligible and :

$s$  = displacement of engine 82 from initial position at static balance,  
 $F$  = force produced by thrust of engine 82,  
 $r_e$  = radius between spin axis 84 and engine 82,

- w = angular velocity in radians per second.
- me = mass of engine 82,
- dx = displacement of center of mass of spacecraft 10d,
- rc = radius between spin axis 84 and crew module 80,
- 5 mc = mass of crew module 80,
- m = total mass of spacecraft 10d at a particular time (which may change as fuel is expended, etc.)

As engine 82 throttles up, the required displacement  $s$  increases with thrust thereby produced. When engine 82 thrust is constant, displacement  $s$  remains constant. As the thrust  
10 returns to zero, displacement  $s$  also decreases to zero. Thus, the translating means can be made to vary the position of engine 82 by the correct amount  $s$  to account for changes in the drive force produced by engine 82. Correspondingly, the center of mass of spacecraft 10d varies between initial center of mass 89 and shifted center of mass 90. Although the location of center of mass of spacecraft 10d varies, it continues to lie along spin axis 84. Since the  
15 rotational forces remain the same, except for the engine thrust moment and the shifted mass moment which cancel each other out, the rotation continues in the preferred rotational direction to define a single spin axis 84 that is unaltered by the off center thrust of engine 82.

The advantages of the present invention over the prior art include, among other advantages, a need for little or no additional mass. There is no need to despin and later  
20 respin the spacecraft for every course maneuver. Such action requires excessive use of reaction-control system (RCS) propellant and possibly the requirement for more massive RCS engines. The apparatus of the present invention is also admirably suited for continuous burn propulsion systems. Such systems may include nuclear electric propulsion and solar electric propulsion engines. With the low thrust-to-weight of such engines, the displacement  
25  $s$ , or other mass displacement which may be used, is small. The apparatus of the present invention also provides a good distance between crew cabin 80 and the engine or engines 82

which may produce harmful particles, radiation, or heat. This distance protects the occupants of the crew cabin (or the payload of scientific instruments) from these potentially deleterious effects of the engine.

An alternative embodiment of the present invention is shown in Fig. 5 for spacecraft 5 10e. In figure 5 the role of moving engine is taken by a moving cabin. In this more practical embodiment the crew cabin moves aft a distance  $s$  and the total vehicle center of mass moves aft distance  $dx$ . The centrifugal force acting on the crew cabin with a line of action a distance  $s-dx$  aft of the center of mass induces a controlled moment equal in magnitude but opposite in direction to the moment created by the engine thrust which has a line of action a 10 distance  $r_e$  from the center of mass.

Solving mathematically for the distance  $s$  required to move the crew cabin by summing up the moments acting on the space craft obtains the previous equation :

$$s = F / (m_e * \omega^2)$$

A derivation follows:

15 Summing centrifugal forces :

$$m_c r_c \omega^2 + \underbrace{(m_{i\_ri}) \omega^2}_{\text{crew side truss}} = \underbrace{(m_{i\_ri}) \omega^2 + m_e r_e \omega^2}_{\text{engine side truss}}$$

Where:

20  $m_{i\_ri}$  = mass and position of truss and other components (fuel tanks) arranged symmetrically or nearly symmetrically along the truss.

Setting centrifugal moments against engine thrust:

$$m_c r_c (s-dx) \omega^2 - \frac{m_{i\_ri}}{crew} dx \omega^2 + m_e r_e dx \omega^2 + \frac{m_{i\_ri}}{engine} dx \omega^2 = F r_e$$

Solving for s :

$$5 \quad s = \frac{F}{m_e \omega^2} \left( \frac{(m_{i\_ri})_{crew} - (m_{i\_ri})_{engine}}{m_c r_c} + 1 \right)$$

If the tanks and comparably lightweight truss masses are assumed to be similarly or symmetrically distributed about the center of mass, then the difference between the  $m_{i\_ri}$  terms approaches zero, especially when compared to the more extreme weight and position  
10 of the crew module  $m_c r_c$ , and one can approximate:

$$s = \frac{F}{m_e \omega^2}$$

Another embodiment of the present invention is shown in Fig. 6 for spacecraft 10f. In Fig. 6, crew module 100 and fuel tank 102 rotate opposite engine 106 and fuel tank 108 around spin axis 110. Spacecraft 10f accelerates in the direction indicated by arrow 112.  
15 Arms 114 and 116 are of unequal length because engine and crew cabin masses 100 and 106 are typically unequal. The length  $r_c$  of arm 116 is the length required for sufficient gravity if the vehicle mostly coasts, or the secant of that length if the vehicle is under continuous propulsion.

The arms are joined by a hinge approximately along the spin axis 110 which bends to  
20 move crew module 100, engine 106, and other related components along an arc path with the approximate same center of rotation. The magnitude and direction of bend (fore or aft) is determined by the mass ratio of engine 106 and crew cabin 100. However, arms 114 and 116

may also bend at different positions along their respective length if the bend induces a moment without changing spin axis 110. Hinges or flexible joints 122 and 128 allow maintenance of the orientation or attitude of crew module 100 and engine 106 with respect to spin axis 110 when arms 114 and 116 bend for inducing a moment. Because the centrifugal forces are equal on both sides of the hinge, so to is the angle 118 of each arm. The center of mass of spacecraft 10e shifts a length dx along spin axis 110. The distance dx extends from center 119 to center 120.

Since the arms are of unequal lengths  $r_c$  and  $r_e$  but with the same angle 118, either the crew cabin 100 or engine 106 will have centrifugal force acting on a line of action more offset from dx than the other. This again creates a moment, which by controlling angle 118 can cancel the thrust of engine 106. Since the rotational forces acting on spacecraft 10e remain the same, except for the engine drive moment and the shifted mass moment that cancel each other out, the plane of rotation of crew module 100 remains orthogonal to spin axis 110. Thus, the principle of operation of spacecraft 10e is the same as that of 10d.

In a similar manner to that shown for spacecraft 10d, the moments acting on spacecraft 10e may be summed to solve for the angle 118 required to offset the unwanted rotation. The angle 118 necessary to induce moments to balance the off center thrust of engine 106 is described mathematically as follows:

$$\text{angle } 118 = \arcsin \left( \frac{F r_e}{w^2 \sum (m_i r_i \bar{r}_i)} \right)$$

where:

$r_e$  = length of engine arm 116,  
 $dx$  = displacement of center of mass along spin axis 110,  
 $F$  = thrust of engine 106,

- $m_i r_i \overline{r_i}$  = each mass  $m_i$  (truss section, fuel tank, crew module, engine, etc.) times its distance  $r_i$  along the arm from the axis of rotation times its displacement vector distance  $\overline{r_i}$  from the center of rotation along either arm 116 (towards crew cabin, positive) or arm 114 (towards engine 82, negative),
- $r_c$  = length of crew module arm 116,
- angle 118 = angle of both arms from a straight line, between them is  $180-2*(\text{angle } 118)$  degrees,
- $w$  = angular velocity in radians per second.

10 With the low thrust of some continuous burn propulsion systems, the displacement angle 118 could be small.

In operation, the present invention allows a very efficient use of mass. Masses of components of the spacecraft used as counterweights, such as the engine, have significant utility outside of their function as a counterweight. Thus, there is little or no deadweight.

15 After deployment of spacecraft 10d, 10e, or 10f, rotation of the craft may be induced to produce the desired gravity. Various thrusters that are typically located over the spacecraft can be used to adjust the initial orientation of the spacecraft. After orientation, the spacecraft main engine, in co-ordination with a mass shifting apparatus as disclosed in Fig. 4, Fig. 5, Fig.6 or some other arrangement, propels the spacecraft in the desired direction. Course changes may be made by altering the orientation of the spacecraft and thus the orientation of the main engines or engine. Various thrusters which are typically located on the spacecraft may be used for this purpose. The action of drive engine producing a drive force in a new direction due to the re-oriented spacecraft effectively alters the course of the spacecraft.

20

The foregoing description of the invention has been directed in primary part to a particular, preferred embodiment in accordance with the requirements of the patent statutes and for purposes of illustration. It will be apparent, however, to those skilled in the art that

25

many modifications and changes in the specifically described apparatus and method for producing an artificial gravitational field may be made without departing from the scope and spirit of the invention. For instance, many schemes may be utilized for shifting mass of the spacecraft and many components of the spacecraft may be used as the mass to be shifted.

5 This method can be used with methods including changing the length and/or mass of the arms or other components of the spacecraft. Several engines firing off center may be used. Several different masses may be moved. The equations used to calculate the amount of mass shifting necessary will be more complex due to the large number of masses and/or forces which may be included in the calculations.

10 These basic equations and techniques could also be used to retain control of any spinning spacecraft in a situation where thrust must be used with a line of action parallel to but not directed through the center of mass. Thrust may be off-center from one of several engines failing, or be desired for the least interference with the sensitive instrumentation comprising much of an unmanned exploratory probe's mass center. Therefore, the invention  
15 is not restricted to the preferred embodiment illustrated, but covers all modifications which may fall within the scope of the invention.

ABSTRACT OF THE DISCLOSURE

An apparatus and method is disclosed for producing an artificial gravitational field in a spacecraft by rotating the same around a spin axis. The centrifugal force thereby created acts as an artificial gravitational force. The apparatus includes an engine which produces a  
5 drive force offset from the spin axis to drive the spacecraft towards a destination. The engine is also used as a counterbalance for a crew cabin for rotation of the spacecraft. Mass of the spacecraft, which may include either the engine or crew cabin, is shifted such that the centrifugal force acting on that mass is no longer directed through the center of mass of the craft. This off-center centrifugal force creates a moment that counterbalances the moment  
10 produced by the off-center drive force to eliminate unwanted rotation which would otherwise be precipitated by the offset drive force.

FIG. 1  
(PRIOR ART)

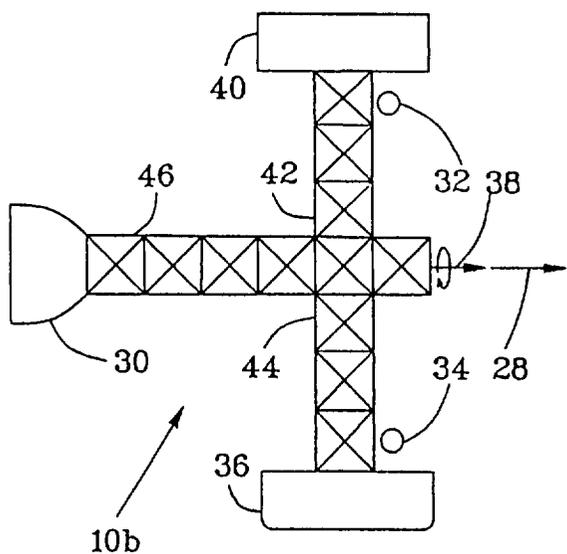
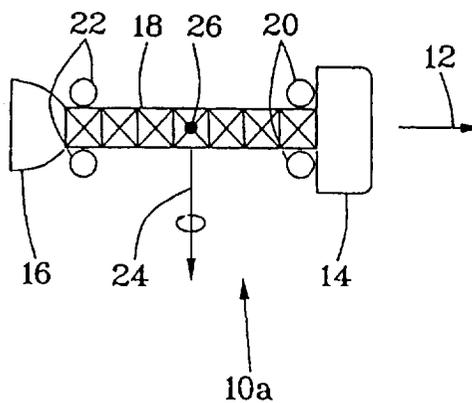
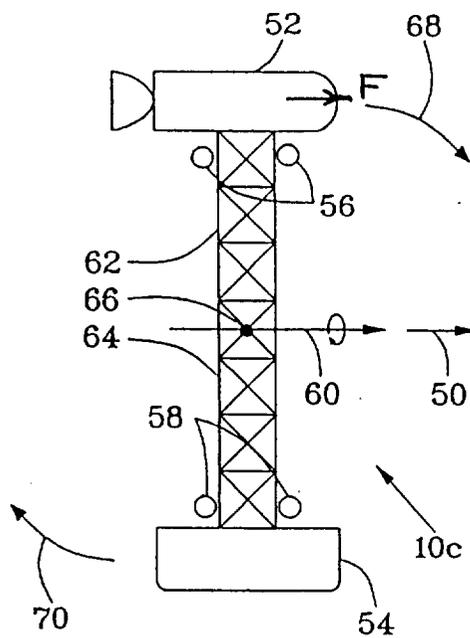


FIG. 2  
(PRIOR ART)

FIG. 3



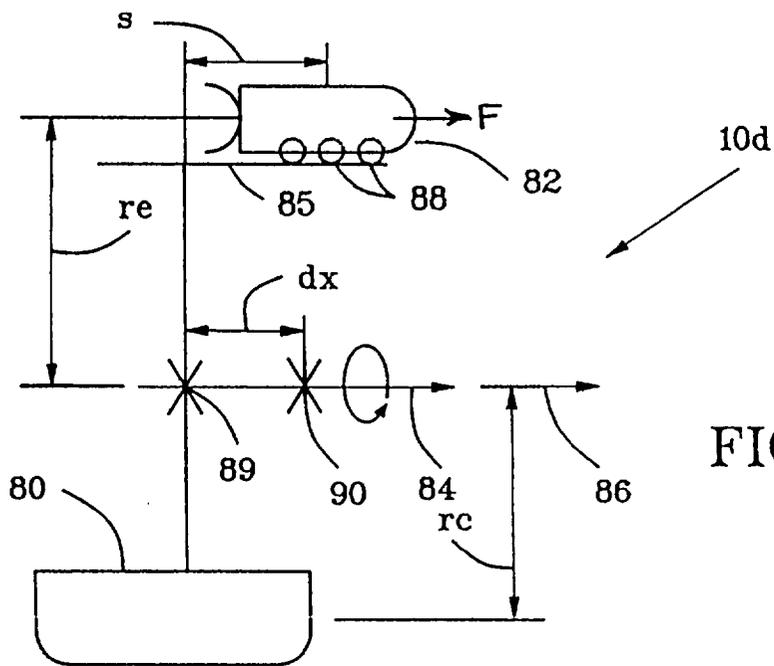


FIG. 4

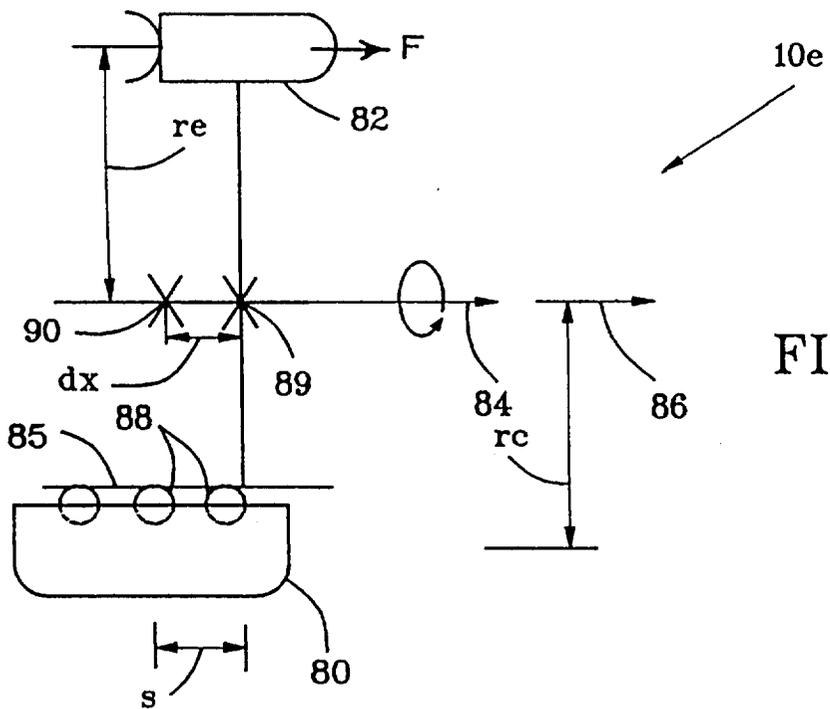


FIG. 5

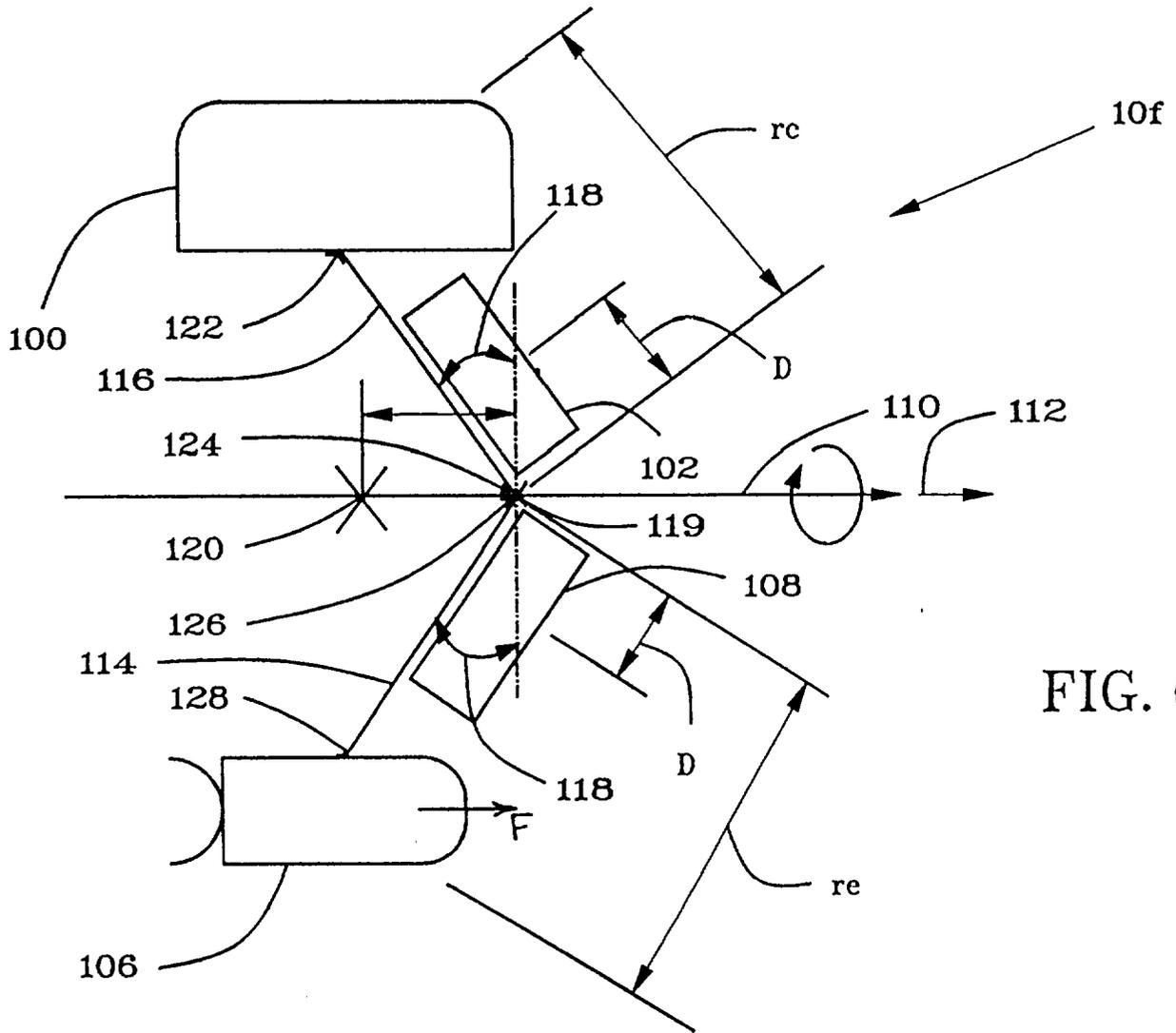


FIG. 6