

# Survey of CVTs for Robot Joints

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# Types of CVTs

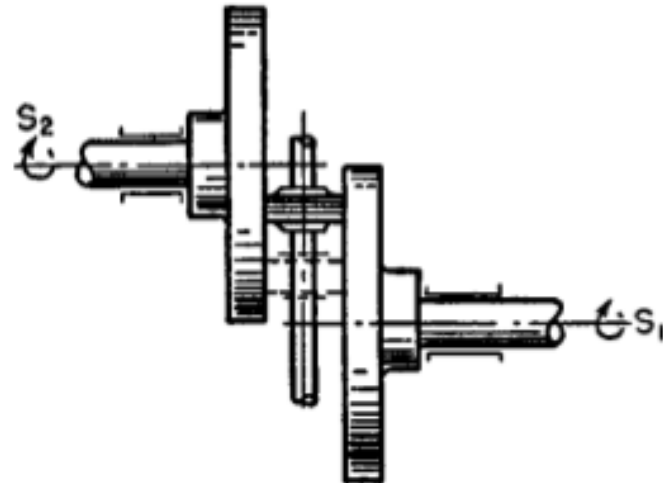
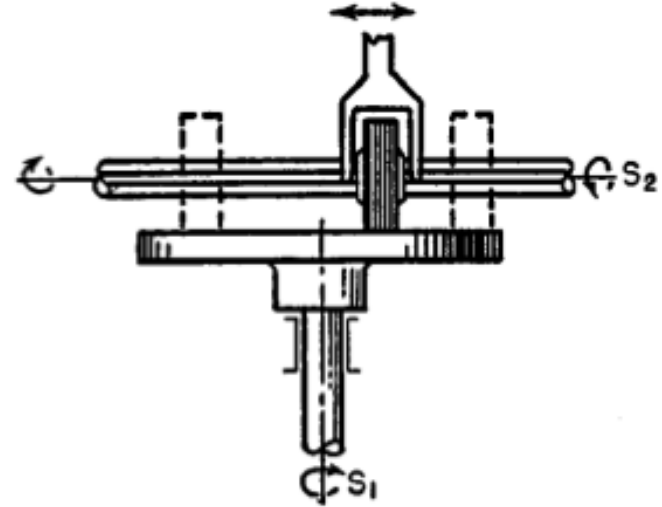
- Friction Drives
- Cone Drives
- Disk Drives
- Spherical Drives
- Pulley-Belt Drives
- Torodial CVT
- Infinitely Variable Transmission (IVT)
- Hydrostatic
- Magnetic – Magnomatic Drive
- Other Concepts

# Friction Drives

- Disk Roller Drives
  - Perform best when reducing speed
  - Compensation for variations in load can be achieved by placing inertia masses on driven end
  - Springs can be used to keep friction parts in contact
  - Typically one friction member and one steel member

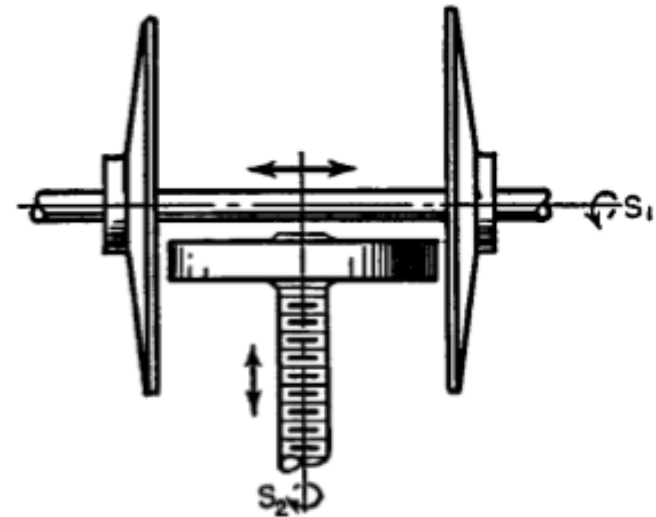
**A)** Speed ratio depends on operating diameter of disk

**B)** Can change speed rapidly because operating diameters of disks change in inverse ratio



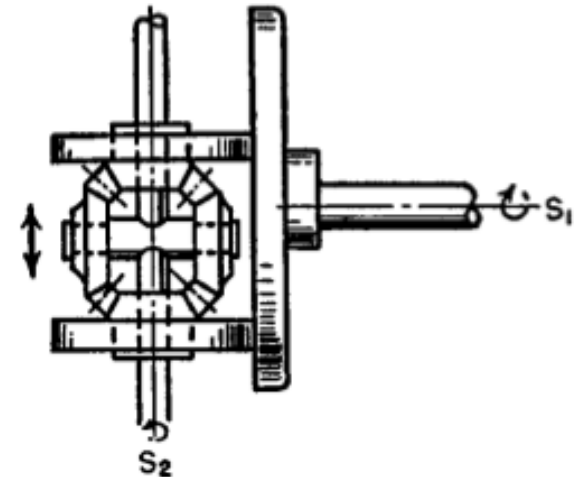
# Friction Drives...

**C)** Two disks mounted to same shaft. Roller can be changed from one disk to the other to change direction. Screw can be moved to change speed



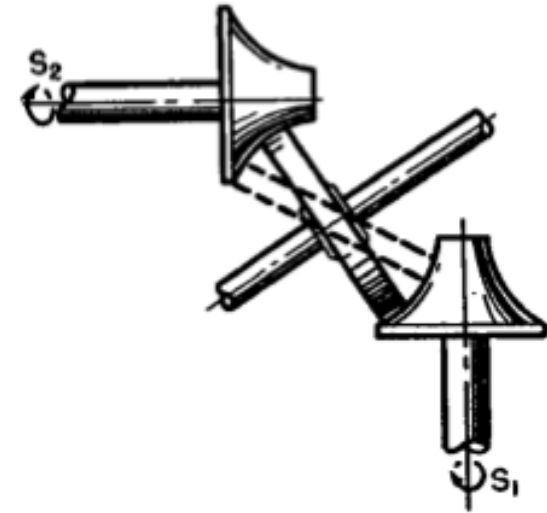
**D)** Disk contacts two differential rollers. Rollers and bevel gears freely rotate on shaft  $s_2$ .

- Pros: accurate adjustment of speed

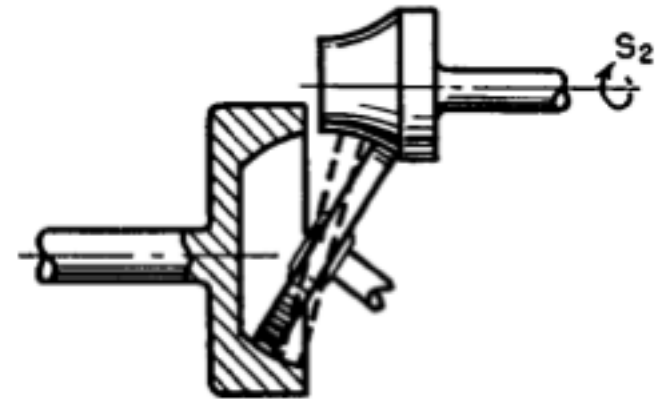


# Friction Drives...

**E)** Two spherical cones on intersecting shafts and a free roller.

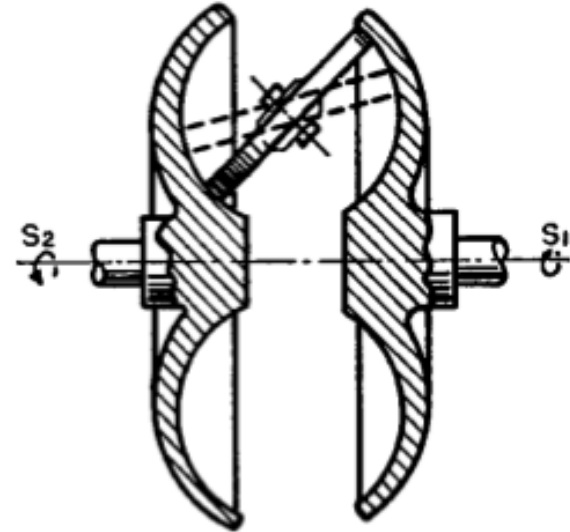


**F)** Spherical cone and groove with a roller. Used for small adjustments in speed

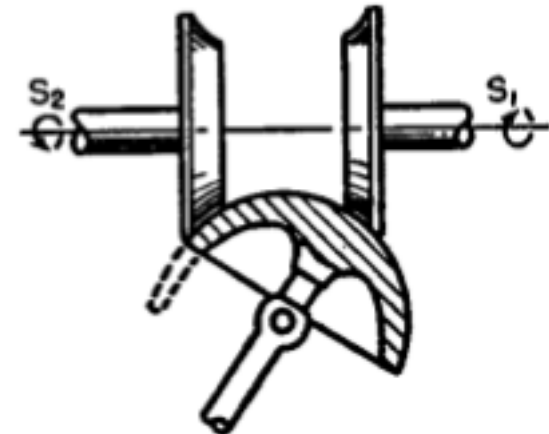


# Friction Drives...

**G)** Two disks with torus contours and free rotating roller



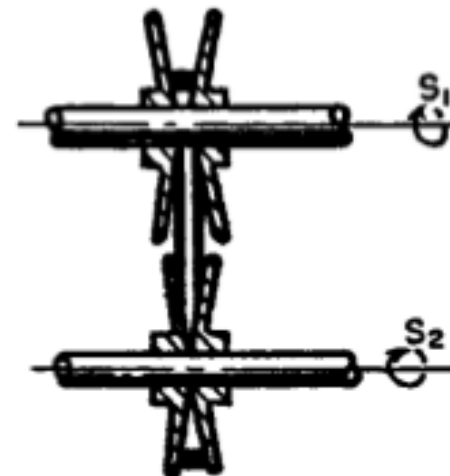
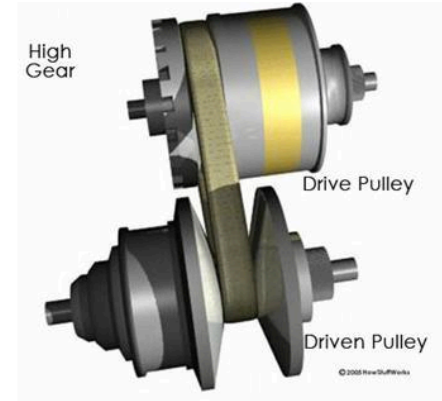
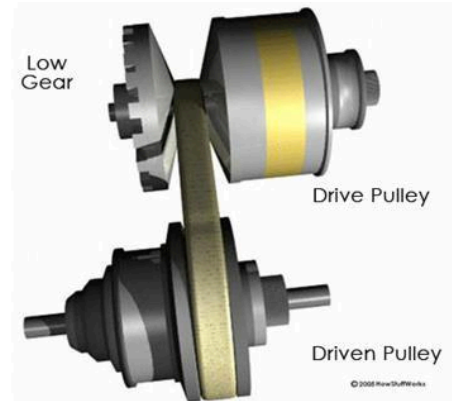
**H)** Two disks with a spherical rotating roller



# Pulley Drives

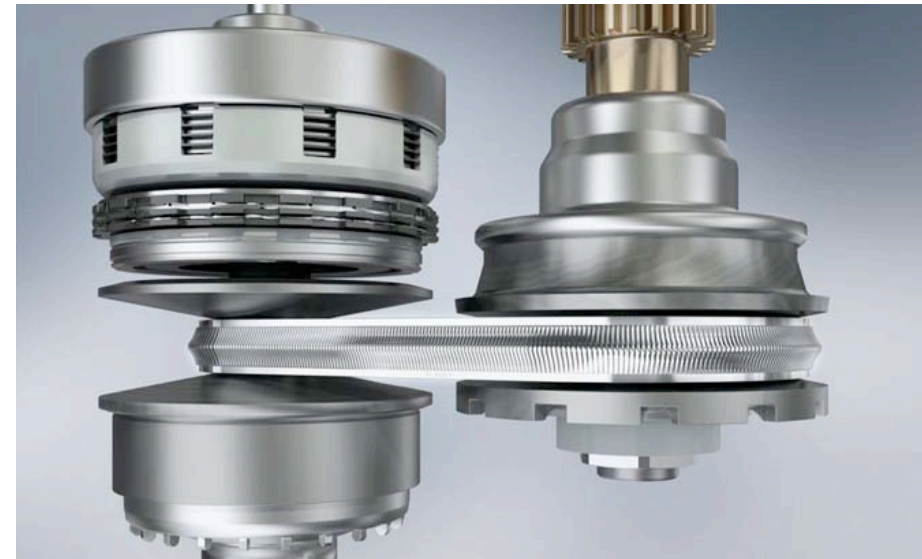
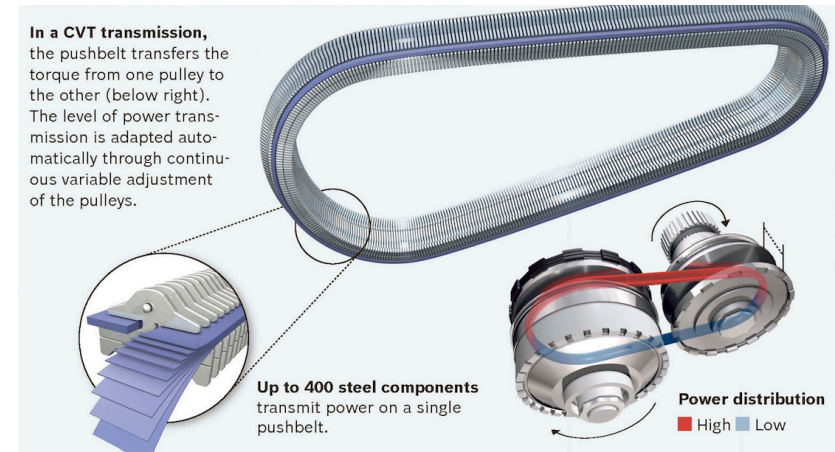
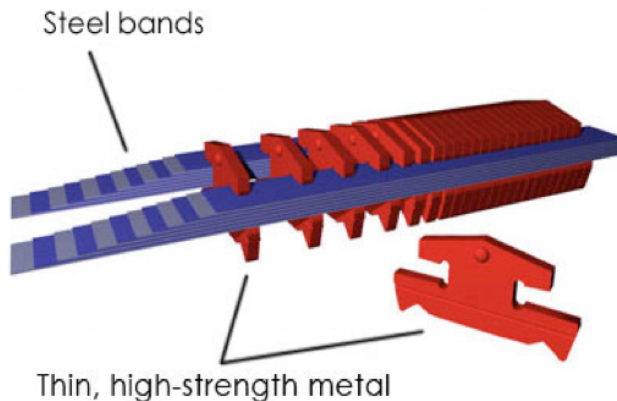
Split pulleys for V-belts. Effective diameter of the belt grip can be adjusted by controlling distance between two parts of the pulley

- Both pulleys have 1 fixed and 1 adjustable pulley half
- Distance between pulley axles remains constant
- The two pulleys are actuated inversely. As one pulley half separates the other pulley contracts because belt length is constant



# Pulley Drives...

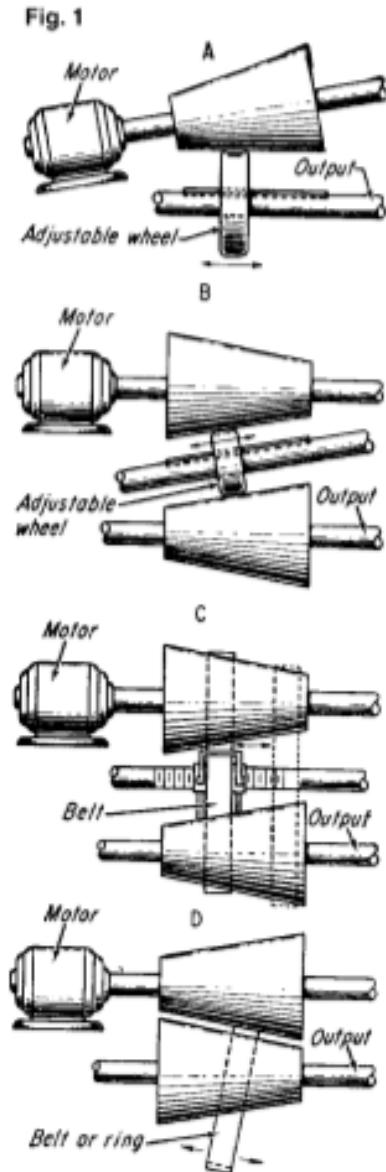
- Rubber Belts can slip and stretch which reduce efficiency
- Thin steel band belts hold together high-strength, bow-tie-shaped pieces of metal
  - Pros: highly durable, quiet, higher torque transmission





# Cone Drives

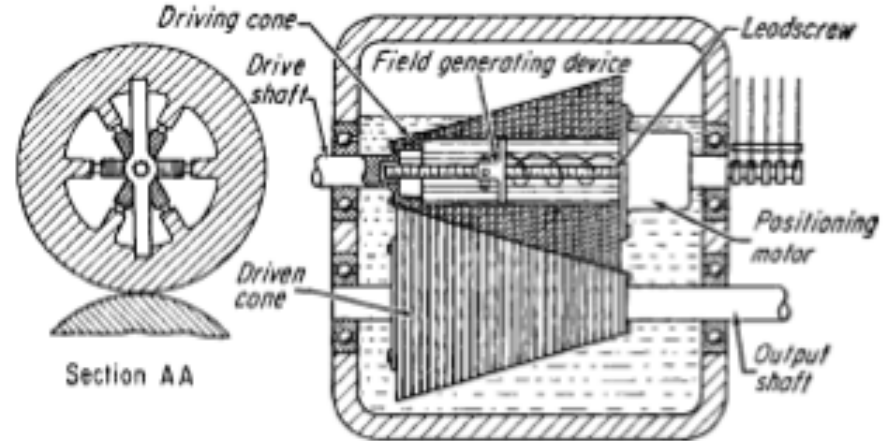
- A. Adjustable Cone Drive
- B. Two Cone
  - Pros: Doubles speed reduction range
  - Cons: both input and output shafts must be spring loaded
- C. Cone-belt: belt envelopes both cones
- D. Cone-belt: long loop endless belt runs between the cones
  - Cons: Belt cross section must be large enough to transmit rated force but width must be minimized to avoid large speed differential over belt width



**E) Electronically Coupled Cones:** Thin laminates of paramagnetic material. Laminates are separated with semi-dielectric materials which localize effect of inductive field.

- There is a field generating device within the driving cone. Adjacent to the cone is a positioning motor for the field generating device. The field created in a particular section of the driving cone induces a magnetic effect in the surrounding lamination.
- This causes the laminate and its opposing lamination to couple and rotate with the drive shaft. The ratio of diameters of the cones, at the point selected by positioning the field-generating component, determines the speed ratio.

Fig. 2

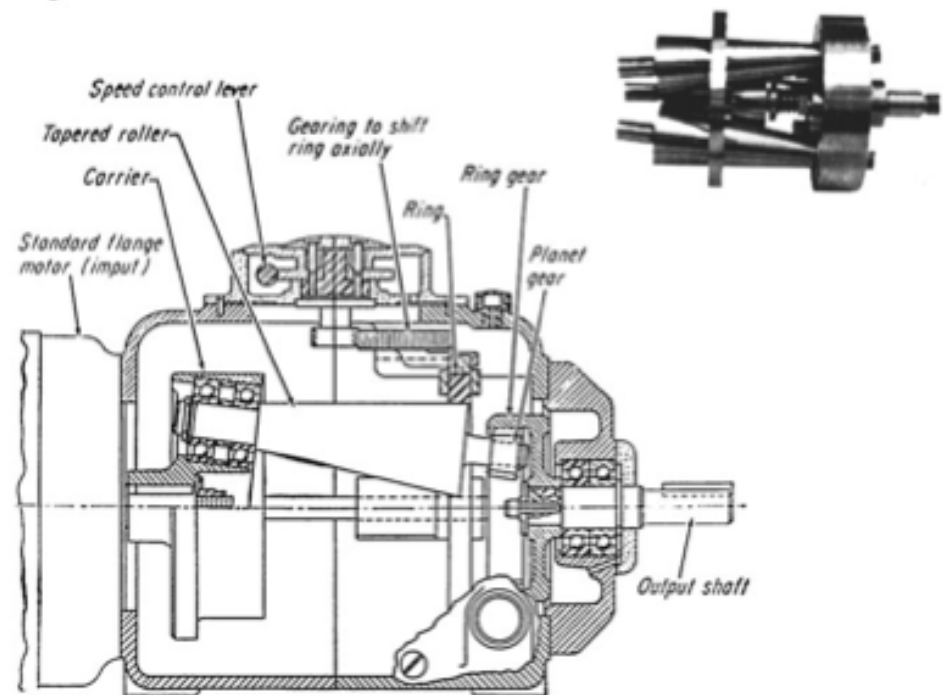


# Cone Drive...

**F) Graham Drive:** Combination of planetary gears with 3 tapered rollers

- Ring positioned axially by cam/gear arrangement
- Drive shaft rotates carrier with tapered rollers which are inclined at angle equal to their taper so outer edges are parallel to centerline of assembly
- Traction pressure between rollers and ring created by centrifugal force or spring loaded rollers
- At end of each roller a pinion meshes with a ring gear which is part of the planetary gear set coupled to the output shaft
  - Pros: 85% efficiency
  - Cons: complex, many components, hard to miniaturize

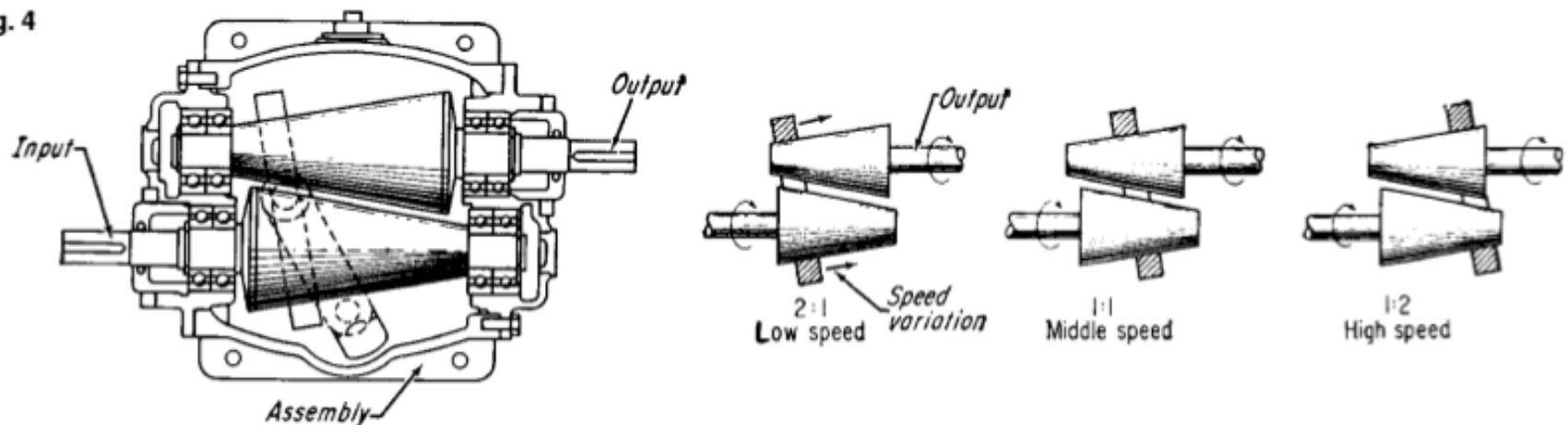
Fig. 3



**G) Cone and Ring Drive:** Two cones encircled by preloaded ring. Shifting the ring axially varies output speed

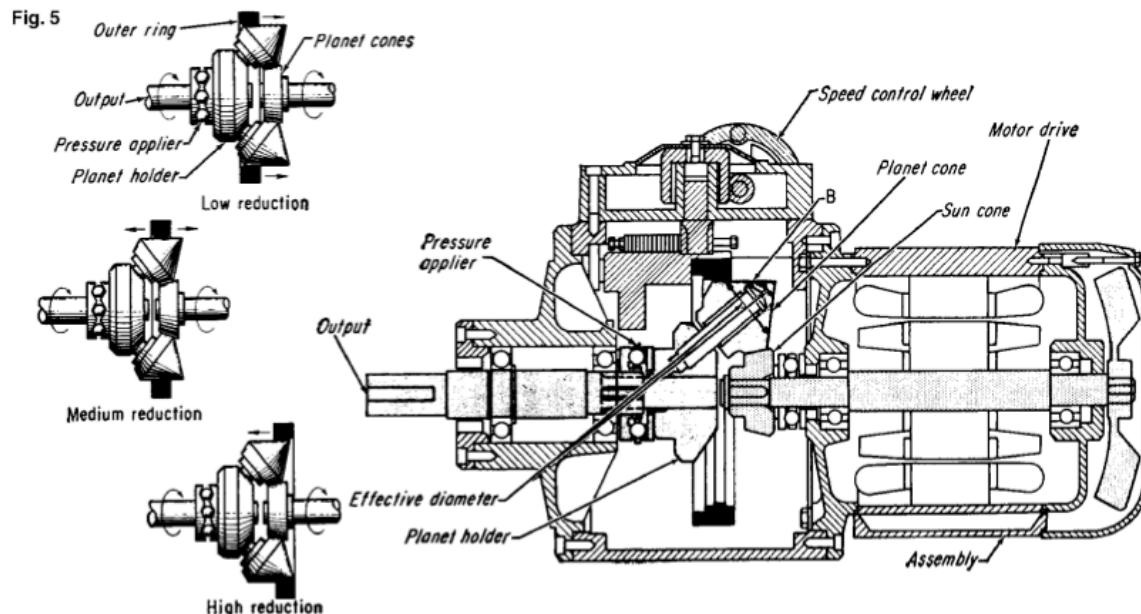
- Pros: Contact pressure between ring and cones increases with load until limit slippage

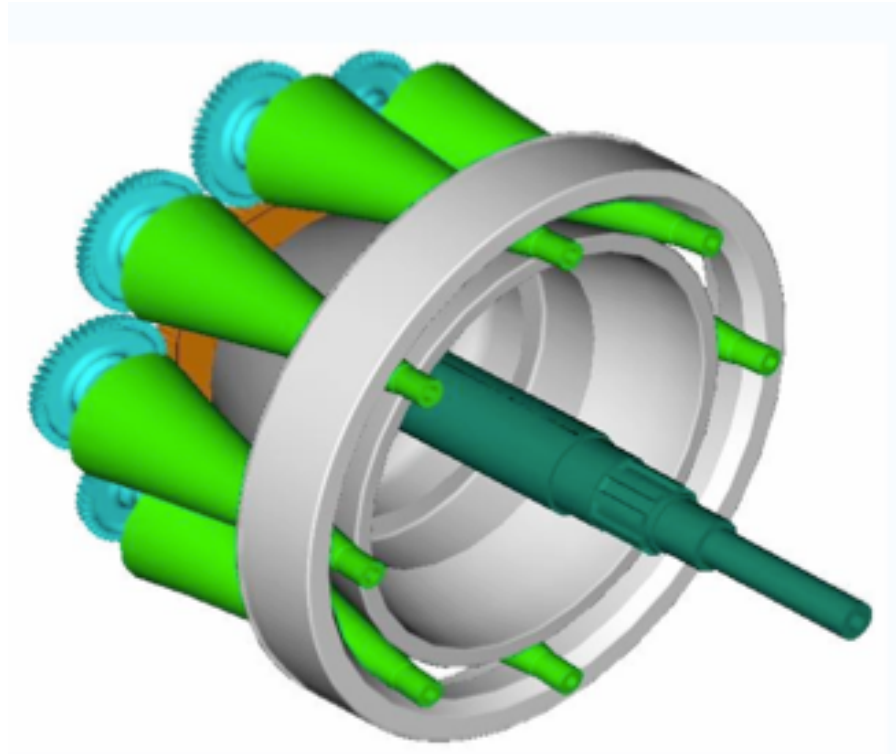
Fig. 4



## H) Planetary-Cone Drive: Planetary gear system with cones instead of gears.

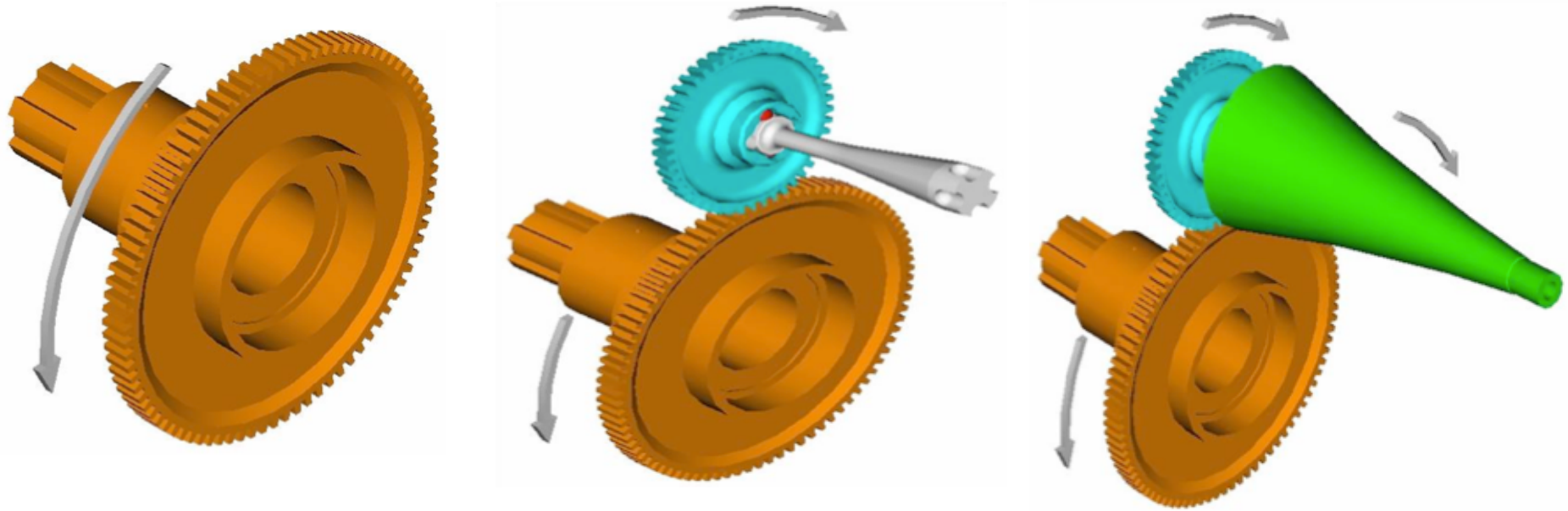
- Planet cones are rotated by the sun cone which is driven by the motor. Planet cones are pressed between an outer non-rotating ring and the planet hold.
- Axial adjustment of ring varies the rotational speed of the cones around their mutual axis
  - Pros: Concentric input and output shafts, ratios from 4:1 to 24:1





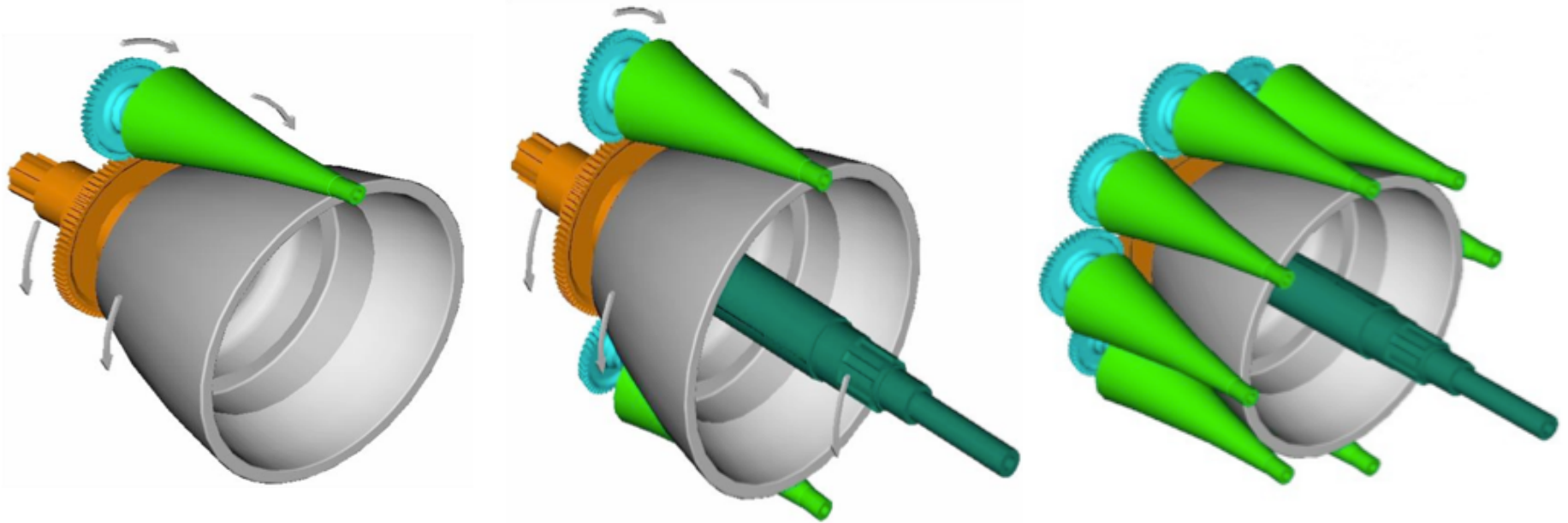
## I) Warko's Cone CVT Link

# Cone Drives...



1. Motor coupled to orange 'solar' gear
2. Orange gear drives blue planet gears (only 1 shown)
3. Each blue planet gear is fixed to a green frustum cone, planet cone, which rotates with the planet gear. The side surface of the planet cone is concave.
  - Uses constant velocity (CV) joint

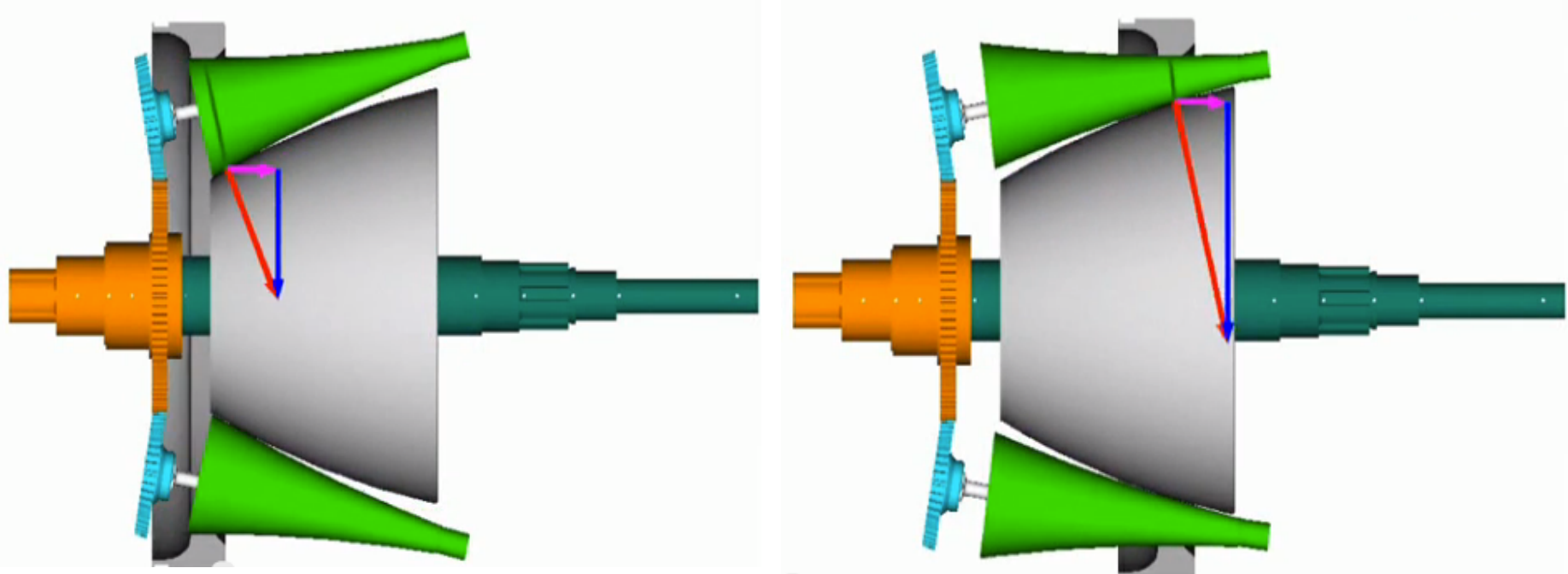
# Cone Drives...



4. The planet cones transmit torque to the gray barrel-shaped hub via friction
5. The motion of the gray barrel is then transmitted to the dark green output shaft by means of direct coupling or additional internal epicyclic or planetary gearing

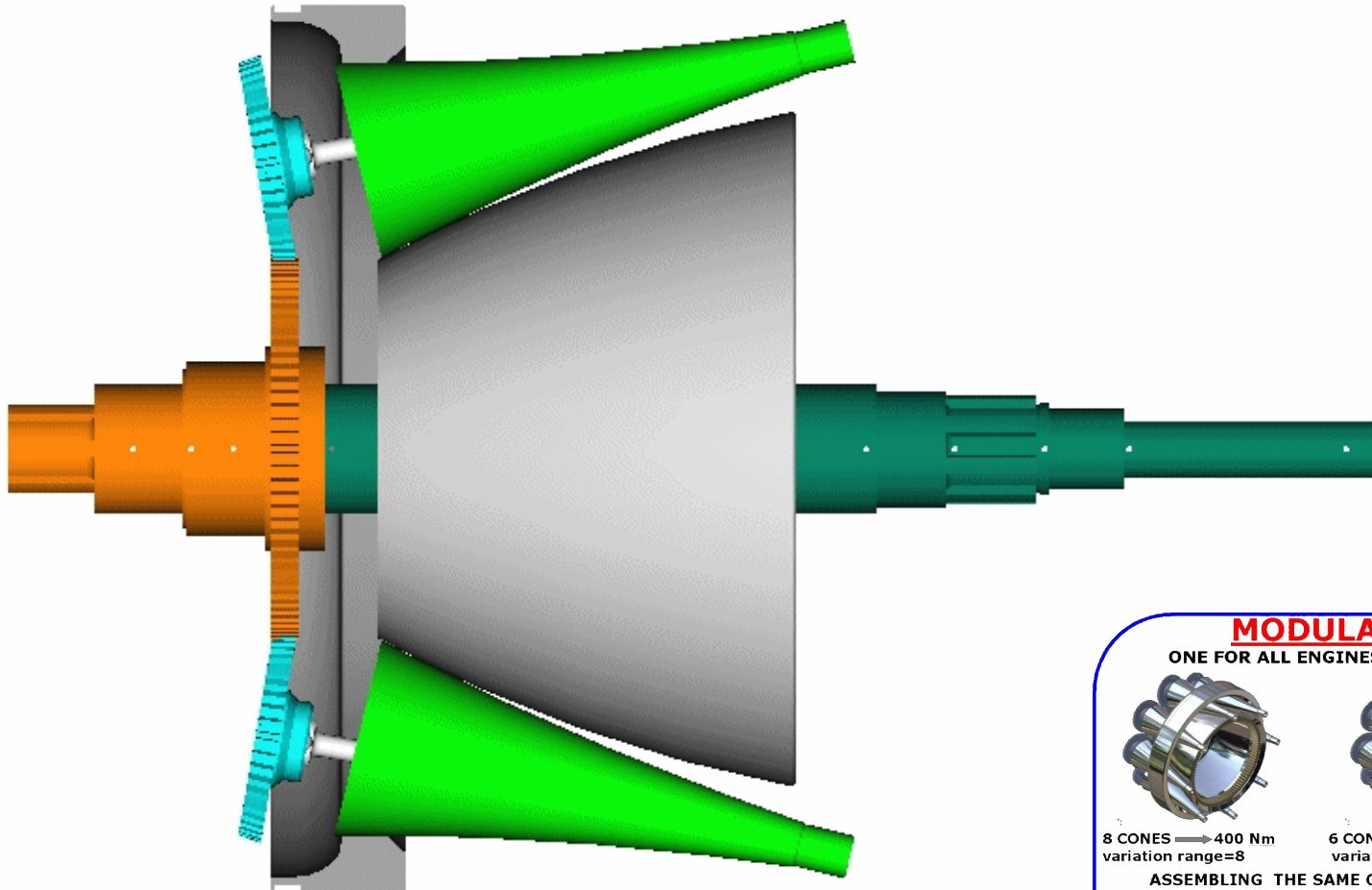


# Cone Drives...



- Transmission ratio is changed by an outer ring that translates in the axial direction. The ring rotates the green cones in a way that forces a different part of the cone to be in contact with the gray hub which is based on the position of the ring.

# Cone Drives...



## **MODULAR = same cone**

ONE FOR ALL ENGINES FROM 60 TO 200 HP AND MORE!



8 CONES → 400 Nm  
variation range=8



6 CONES → 300 Nm  
variation range=8



4 CONES → 200 Nm  
variation range=8

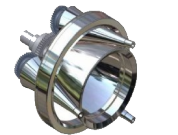
ASSEMBLING THE SAME CONE WITH DIFFERENT RING AND HUB



6 CONES → 240 Nm  
variation range=10



4 CONES → 180 Nm  
variation range=10

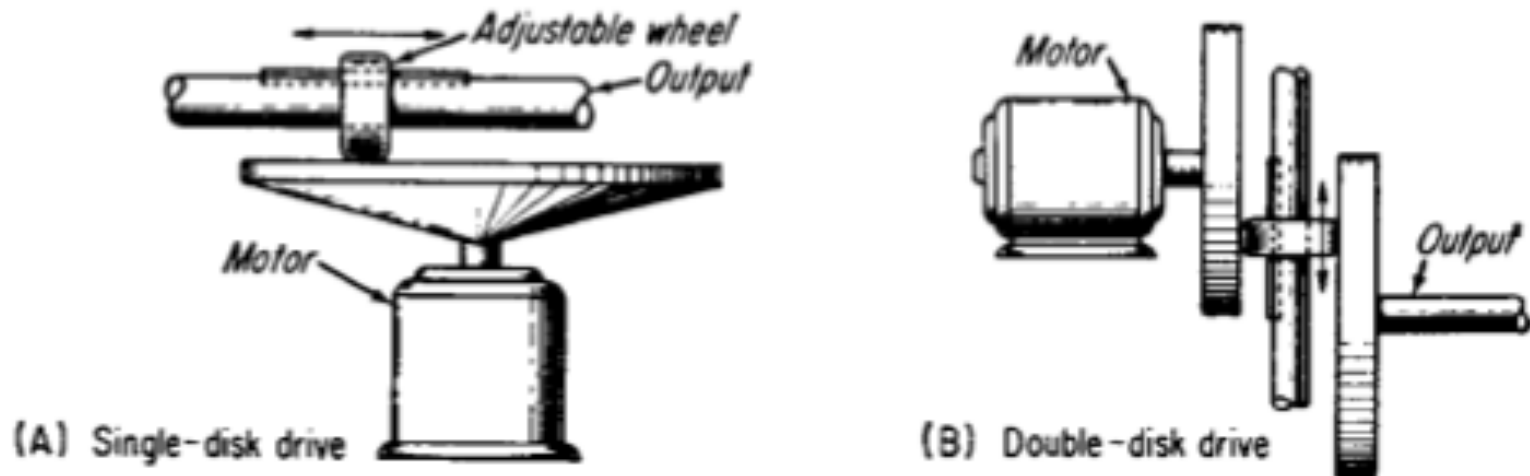


3 CONES → 120 Nm  
variation range=10

**A) Adjustable Disk drive:** Wheel is made of high friction material and the disk is made of steel

- Cons: relatively high slippage limits transmitted torques
- Pros: wheel can move over center of disk to create infinite speed adjustment

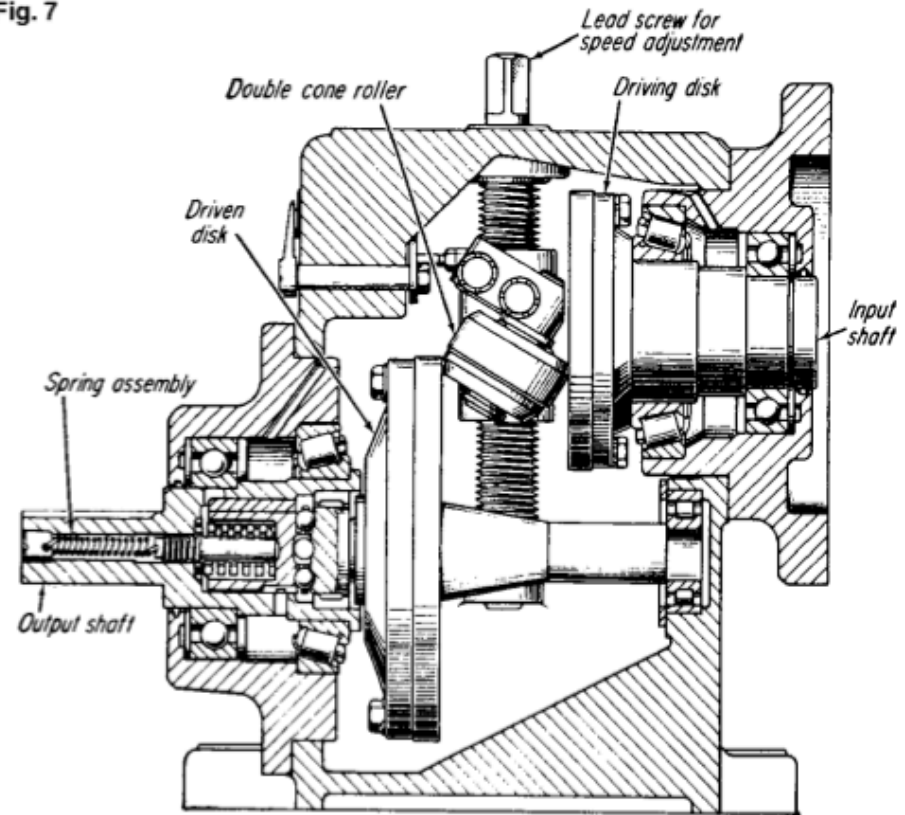
Fig. 6



**B) Spring Loaded Disk Drive:** To reduce slippage, the contact force between the rollers and disks is increased with spring assembly in the output shaft. Lead screw is actuated to shift cone roller in vertical direction to change speed ratio

- Pros: reduced slippage, increased torque transmission capability
- Cons: complex many parts, difficult to miniaturize

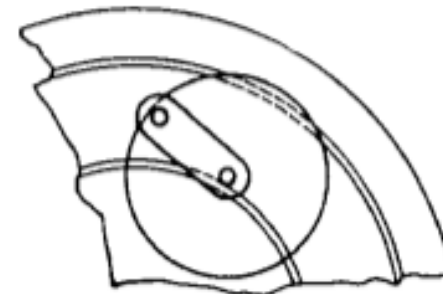
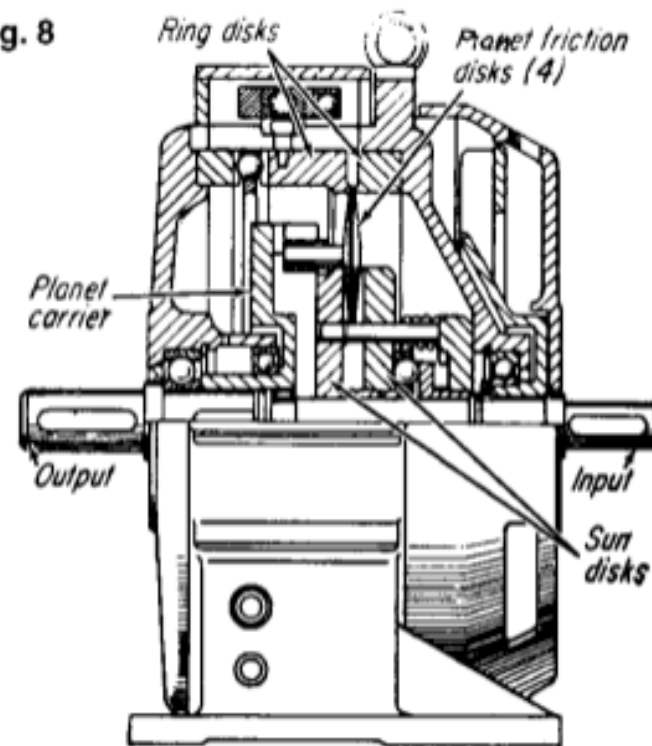
Fig. 7



## C) Planetary Disk Drive: four planet disks replace planet gears

- Planets mounted on levers which control radial position
- Ring and sun disks are spring loaded

Fig. 8



# Ring Drives

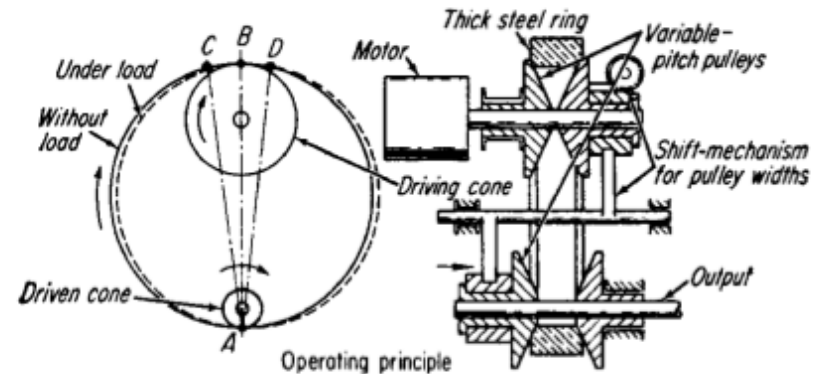
**A) Ring and Pulley Drive:** thick steel ring encircles two variable width pulleys

**B) Double Ring Drive:** Two steel traction rings engage two sets of disk mounted on separate shafts. Speed is changed by tilting ring support cage

- Outer disk must be under compression load from spring system

Fig. 9

A



a

b

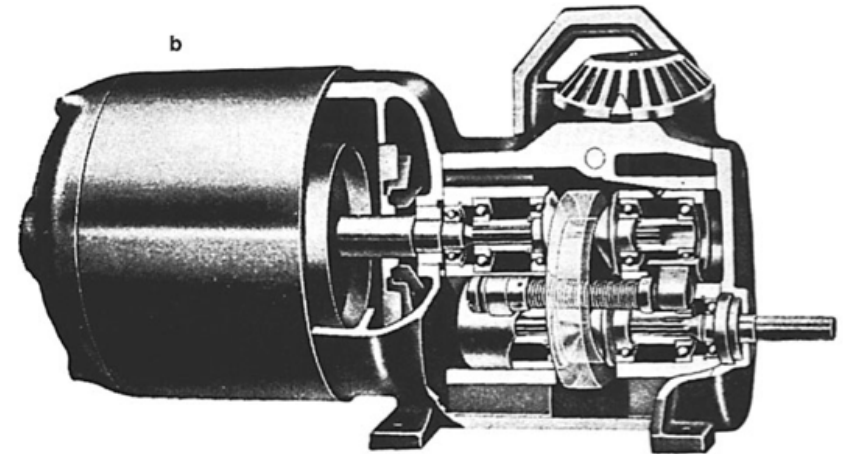
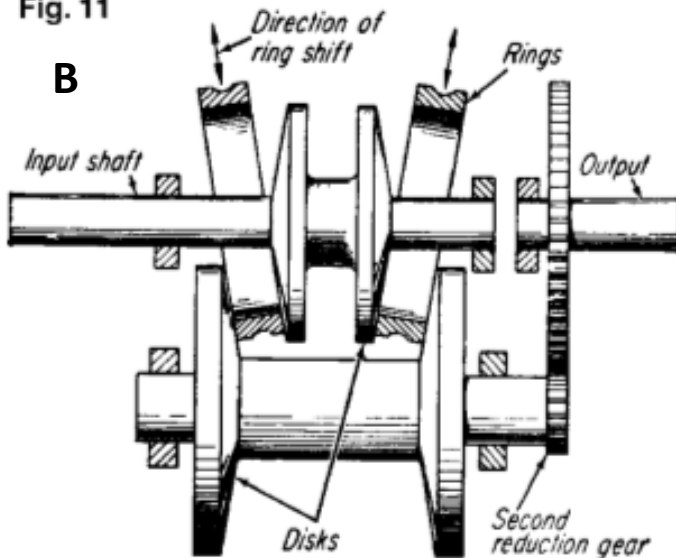


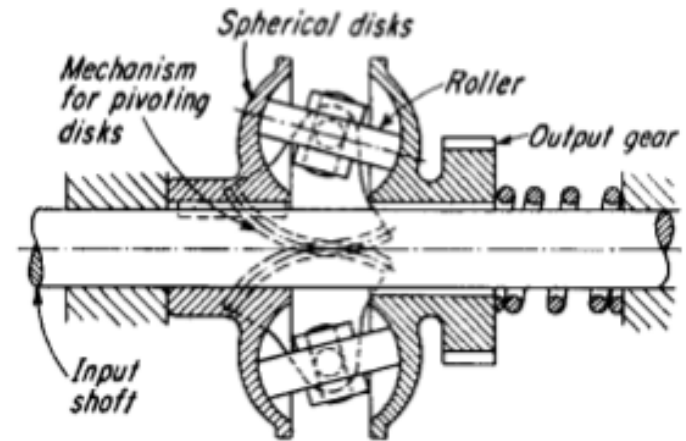
Fig. 11

B



**A) Sphere and Disk Drive:** speed variations achieved by changing angle that rollers make in contacting spherical disks. Sheaves are loaded together by helical spring.

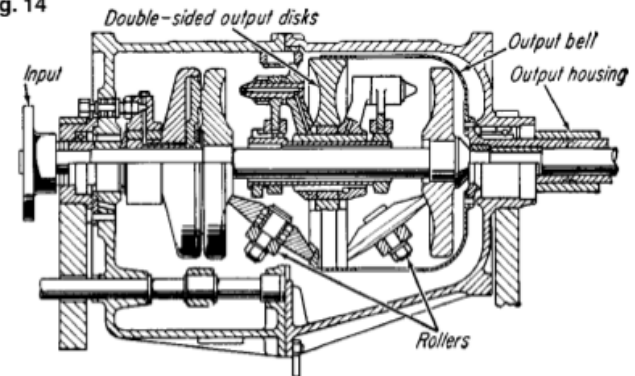
Fig. 12



## B) Double Sphere Drive

- Pros: higher reduction ratios, reduces operating stress and wear

Fig. 14



# Spherical Drives...

**C) Tilting-ball Drive:** Power transmitted between disks by steel balls whose rotational axes can be tilted to change relative lengths of the two contact paths around the balls

- NuVinci Drive
- Efficiency decreases as reduction ration increases
  - Cons: complex design, limited gear ration range, bad efficiency
  - Pros: Concentric input/output shafts

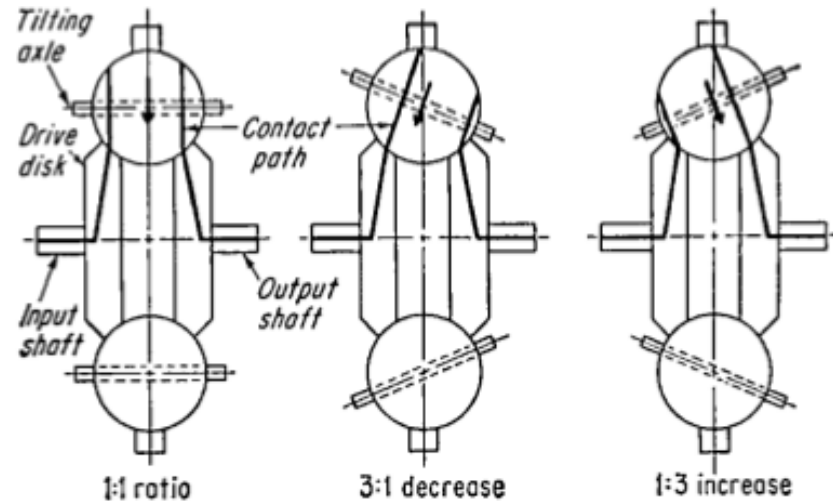
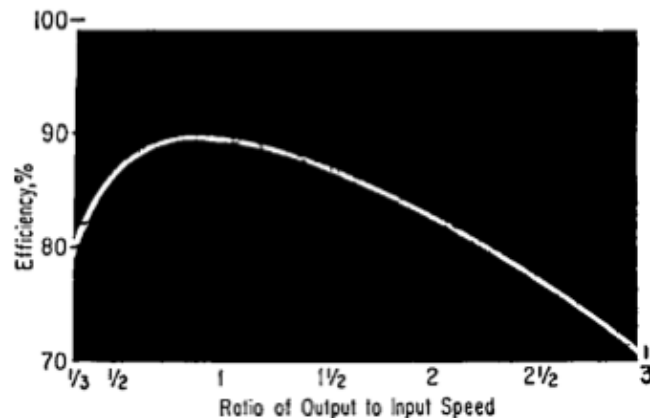
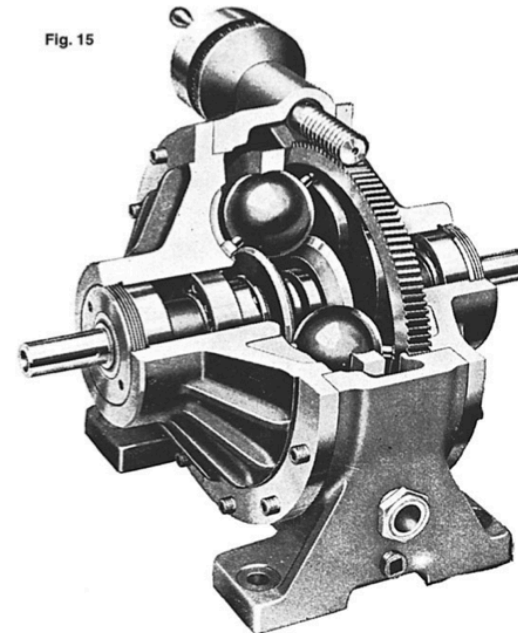


Fig. 15





# Spherical Drives...

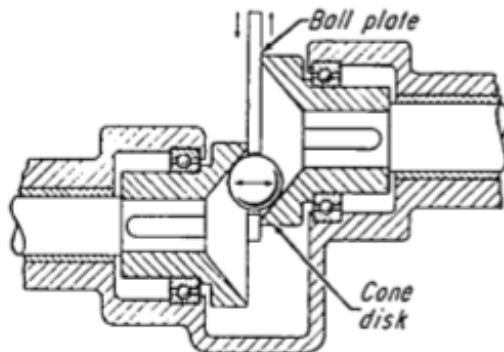
**D) Sphere and Roller Drive:** roller with spherical end surfaces eccentrically mounted between coaxial input and output spherical disks. Speed ratio adjusted by changing angular position of the roller

**E) Ball and Cone Drive:** Two opposing cones with  $90^\circ$  internal vertex angles fixed to each shaft. Shafts are preloaded against each other. Speed variation obtained by positioning the ball that contacts the cone

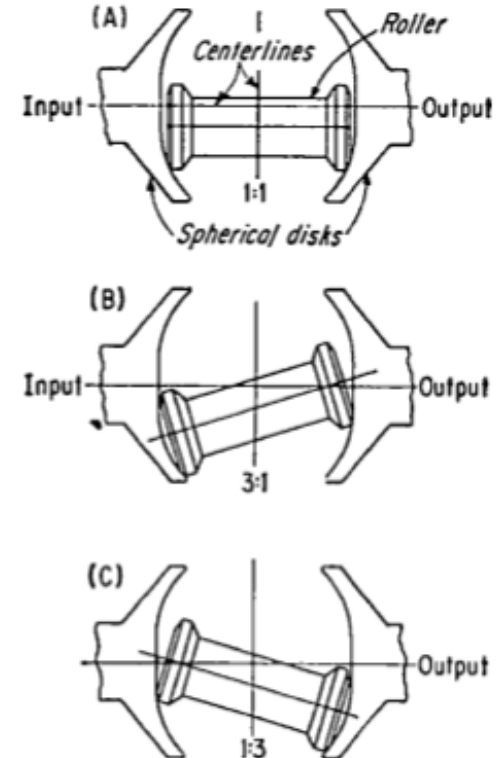
- Cons: Offset shafts, traction fluid

Fig. 17

E



D

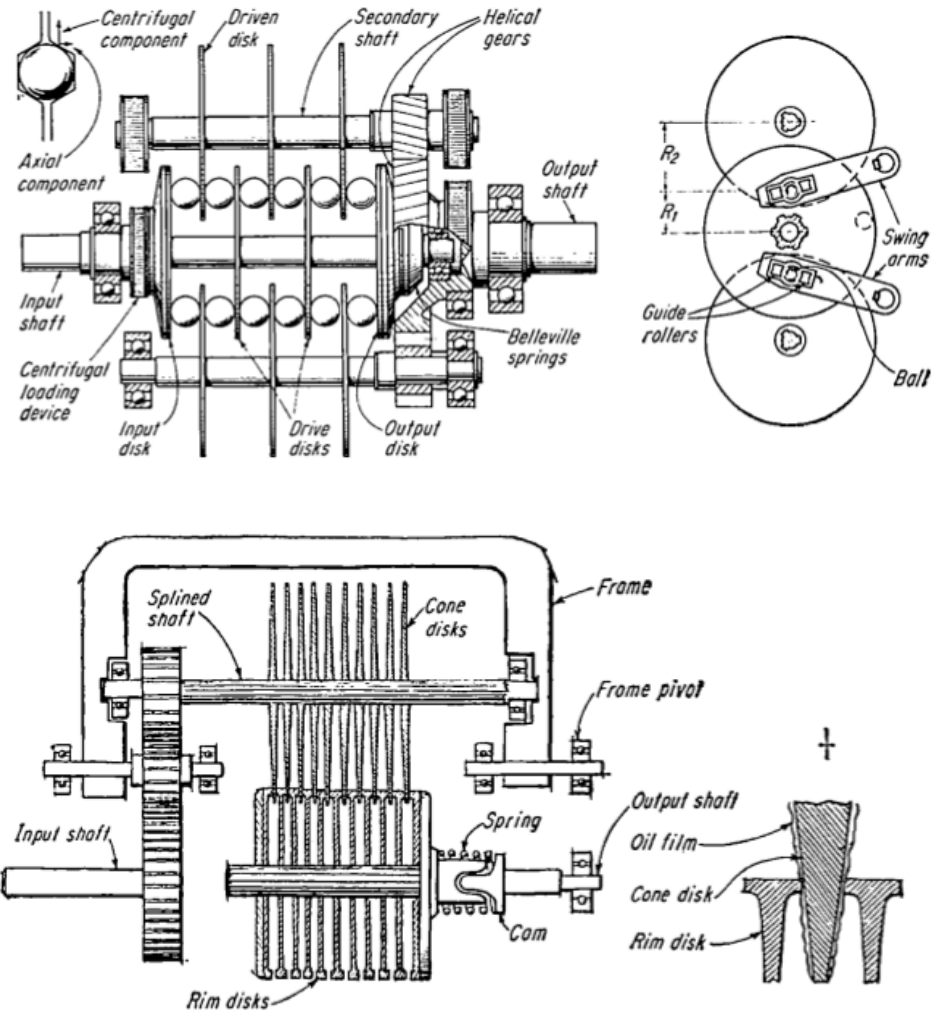


# Multiple Disk Drives

**A) Ball and Disk Drive:** Friction disks mounted on spline shafts to allow axial movement. Steel balls carried by swing arms rotate on guide rollers and are in contact with driving and driven disks. Position of balls controls ratio of contact radii which determines transmission ratio

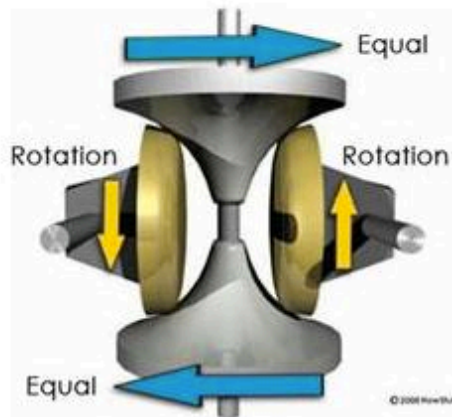
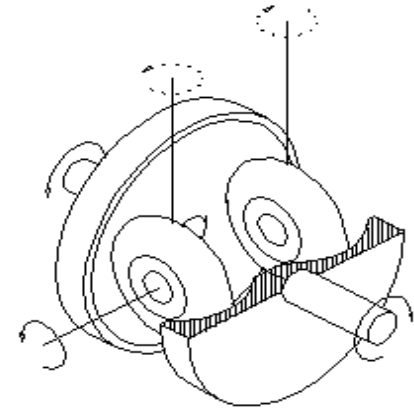
**B) Oil-Coated Disks:** Power transmitted without metal-to-metal contact at 85% efficiency. Interleaved disks are coated with oil. Cone disks transmit motion to rim disks by shearing the molecules of high viscosity oil film. Speed changed by moving cones radially toward the rim disks. Spring cam on output shaft maintains pressure of disks at all times

Fig. 18

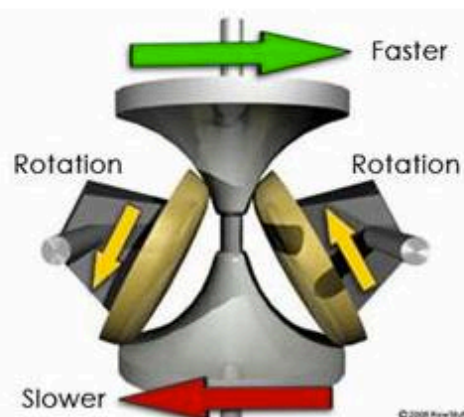


# Torodial CVT

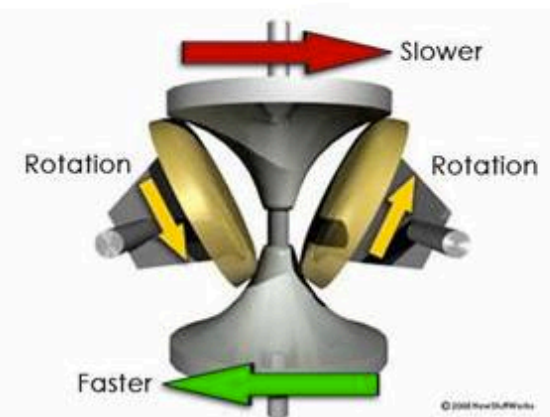
- Pros: concentric input/output shafts
- Cons: very precise machining tolerances



**Fig 1.3a**

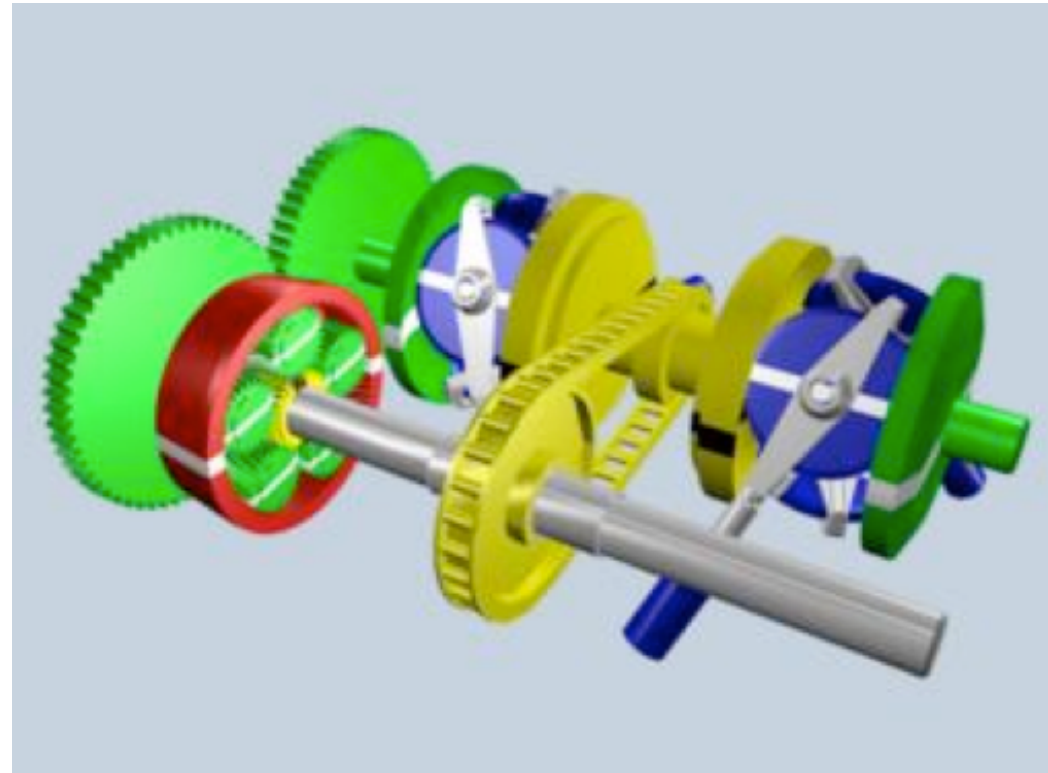


**Fig 1.3b**



**Fig 1.3c**

- Composed of a CVT in combination with a planetary gear system.
- Infinite ratios can be generated by driving the planetary or differential gearset
- Torotrak CVT
- Link

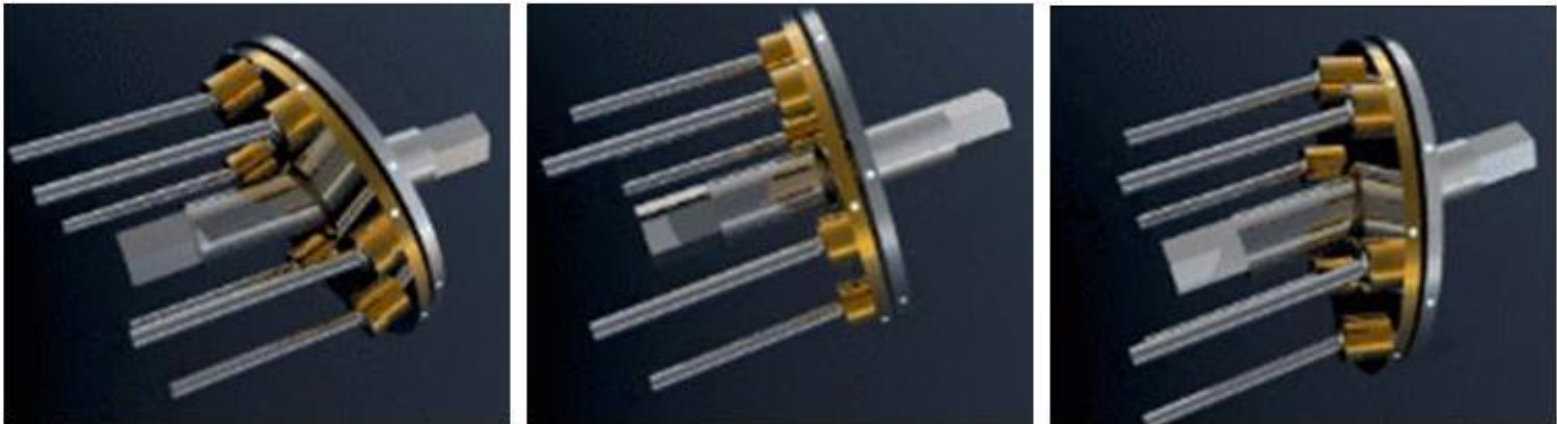


# Variable Toothed Drive

- Not a true CVT but has a large number (usually 49) of discrete and incremental ratios
- Toothed wheel positively engages with chain where toothed wheel can add or subtract a tooth at a time in order to alter its ratio relative to the chain its driving
  - Pros: very small frictional losses, not limited by rollers
  - Cons: challenging design of variable tooth system to add/subtract a tooth precisely

# Hydrostatic CVT

- The Hydrostatic CVT works on nearly the same design as the NuVinci except the balls that would allow the gearing ratio to change have been replaced by rods pin joined with the swash plate. Mechanical movement changes hydrostatic pressure and that pressure further makes mechanical changes which in turn changes the gearing ratio between the driver and driven shaft.



# Magnetic CVT

- Drive consists of a stator which accommodates a 3-phase winding, and three concentric rotors: control rotor, input and output rotors. The control rotor has ( $P_c$ ) number of pole-pairs on the outer surfaces and ( $P_t$ ) number of pole-pairs of permanent magnets on its inner surface. The magnets on the outer surface of the control rotor interact with the currents in the 3-phase stator winding to produce torque in the same way as conventional brushless permanent magnet (PM) machines. The magnets on the inner surface of the control rotor interact with the input and output rotors to produce magnetic gearing action. It has been shown that by controlling the speed of the control rotor, the gear ratio between the output rotor and input rotor can be varied.

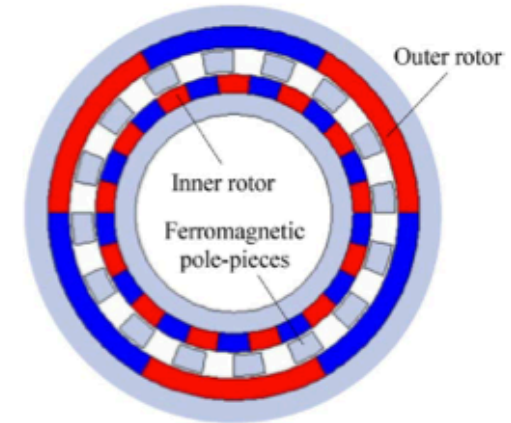


Fig. 1. Schematic of magnetic gears.

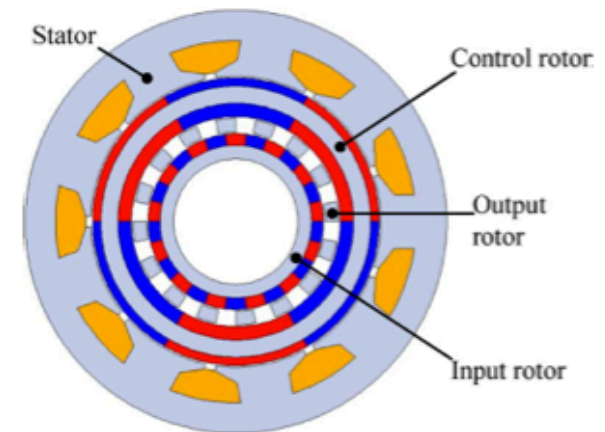


Fig. 2. Schematic of magnetic continuously variable transmission.

# Other Concepts

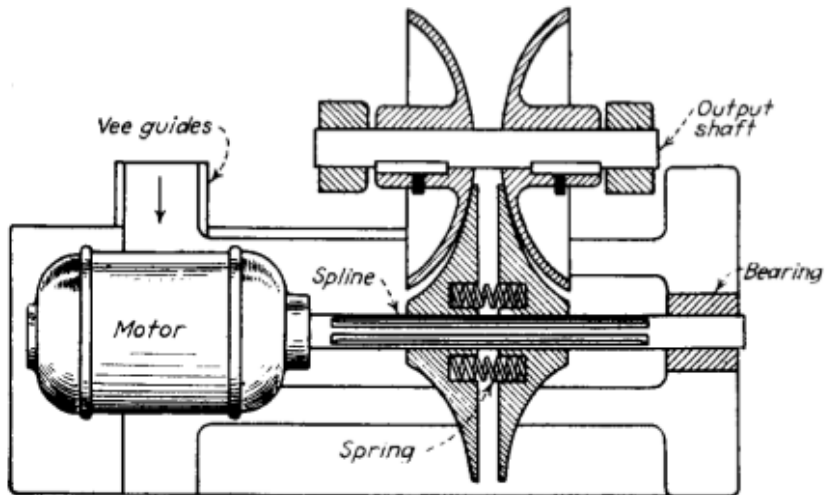


Fig. 25

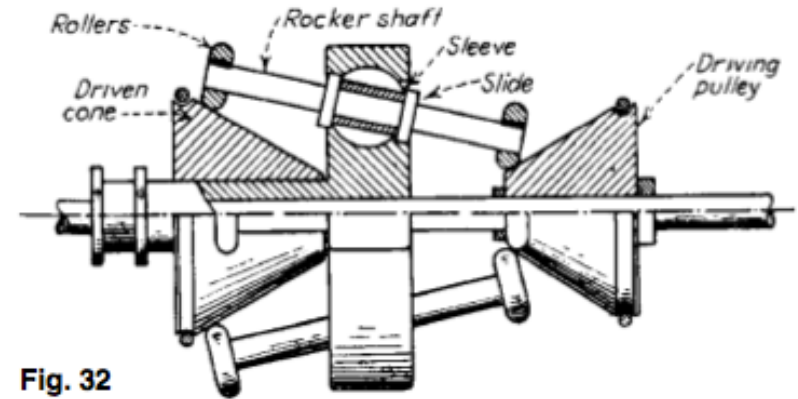


Fig. 32

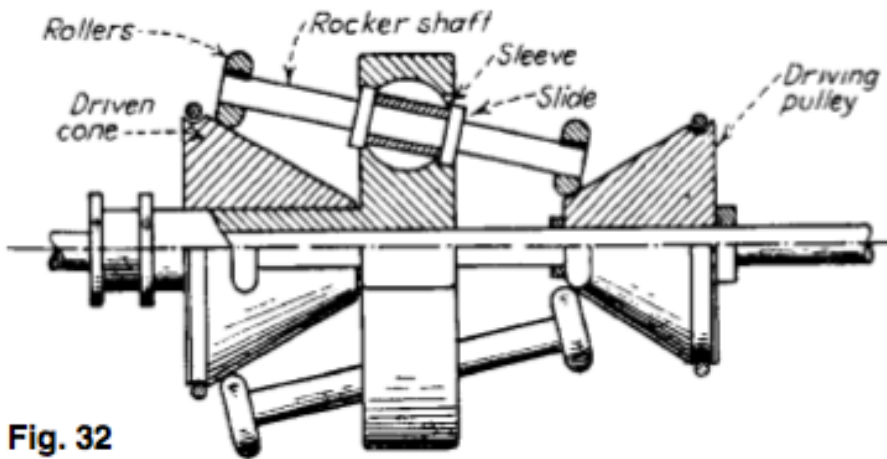


Fig. 32

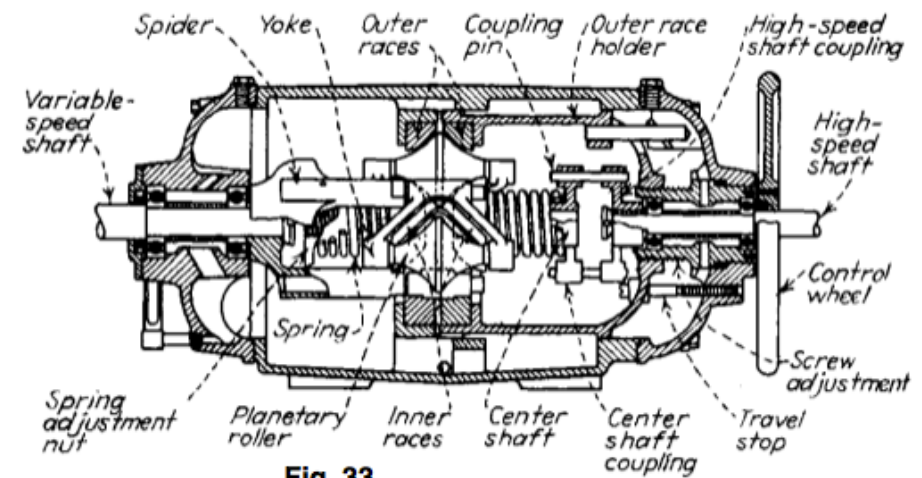


Fig. 33