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Novel Infinitely Variable Transmission Allowing Efficient Transmission Ratio Variations at Rest

Christophe Everarts, Bruno Dehez and Renaud Ronsse

***Abstract*— Recent studies showed that Continuously Variable Transmissions (CVT) and Infinitely Variable Transmissions (IVT) can considerably improve the locomotion efficiency in legged robot. A CVT is a transmission whose ratio can be continuously varied and an IVT is a transmission whose ratio can be continuously varied from positive to negative values. However, efficient use of such transmissions in walking applications requires changing the transmission ratio at a minimal energy cost, even at rest, i.e. when the input shaft is not rotating. This contribution proposes a novel CVT and IVT principle which can achieve such ratio variations at rest. The presented CVT is a modified planetary gear, whose planets are conical and mounted on inclined shafts, and whose ring is made of contiguous diabolo-shaped rollers. This configuration enables the control of the transmission ratio by adjusting the point of contact between the cones and rollers that comprise the ring. A traditional planetary gear system can be added to the CVT to form an IVT.**

I. INTRODUCTION

Legged locomotion involves both high and low torques in both directions within a single gait cycle, together with large variations in the joints velocity. This results in large fluctuations of the lower limb joint power profiles [1], [2]. Moreover, the power profile of all leg joints switches several times between positive and negative values as illustrated in Fig. 1 for the hip, knee and ankle of a 75 kg healthy walker during one step [1].

Humanoid robots aim to reproduce this dynamical behavior of human joints, and therefore must provide similar power profiles. This is even more critical in the development of lower-limb prostheses, whose ideal kinematics and dynamics should be close to the one of their human user. One architecture for actuating artificial leg joints leverages Series Elastic Actuators, e.g. the ankle-foot prosthesis developed by [3]. It includes a serial compliant element between the transmission output and the load. The compliant element has the ability to store and release energy and then provides a fraction of the fluctuating power. With this mechanism, the power profile provided by the motor is flattened with respect to the one transmitted to the load. However, the selected actuator stiffness typically optimizes this "power filtering" for only a single cadence [4].

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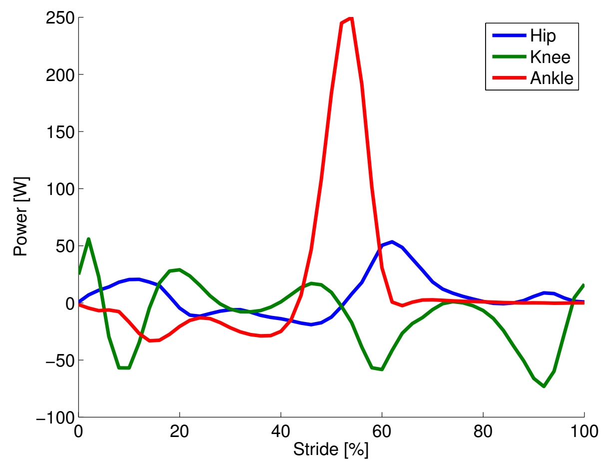


Fig. 1. Lower limb joints power. Data adapted from [1] for a 75 kg walker.

Recent studies showed that the use of Continuously Variable Transmissions (CVT) or Infinitely Variable Transmissions (IVT) can drastically improve the motor efficiency, for a large range of walking cadences [5]–[7]. A CVT is a transmission whose transmission ratio can be continuously varied. An IVT is a CVT with a ratio changing range crossing zero, i.e. from negative to positive values. In most cases, an IVT is implemented by adding a planetary gear at the output of a CVT [8], [9]. Indeed, a planetary gear can shift the ratio range of a CVT around zero.

In the literature, two different strategies of using CVTs or IVTs are proposed to improve efficiency of lower limb joints. The first is based on the use of a CVT between a motor and a series elastic element [7]. This concept allows the motor to operate at lower torque and at speed regimes of higher efficiency. The second is based on the use of an IVT between the elastic element and the load, in order to produce the desired output torque from an arbitrary level of energy in the the elastic element, typically a spring [5], [6]. The idea is to operate the motor within a constant torque-velocity regime corresponding to its maximum efficiency. The motor feeds the spring with almost constant power and the desired torque is applied to the load by adjusting the IVT ratio. This concept is analogous to using a flywheel in applications requiring high power peaks with a constant input power. A critical difference is that the flywheel are heavy and stores kinetic energy, while the spring are lightweight and stores potential energy.

In order to bridge the gap between simulations and reality, these concepts require a CVT or IVT design being small, lightweight, and efficient at both power transfer and ratio control. Various implementations of CVTs and IVTs are proposed in the literature [10]–[19]. The most common are toroidal systems [10]–[12]. This kind of CVT is remarkably efficient for automobile applications but they are complex, heavy, difficult to miniaturize and the transmission ratio cannot be efficiently changed at rest. CVTs and IVTs for smaller applications can be found, but they cannot operate continuous rotations, their range of motion being limited [13]–[19].

The present paper proposes a new mechanism of CVT that was developed for robotic legged locomotion. This novel CVT can further be turned into an IVT by adding a planetary gear at the output. This paper is organized as follows. In Section II, the transmission principle is presented. In Section III, an implementation of this concept, and a prototype of the IVT are described. In Section IV, preliminary experiments on the prototype are reported. The main results show that the output velocity can vary from negative to positive values while maintaining a constant input velocity. This experiment validates the model by showing good agreement between the expected and actual transmission ratios. Finally, section V concludes the paper with a discussion on the experimental results, and opens perspectives for improvements.

II. Working Principle

This section develops the kinematic model of a new concept of IVT based on the combination of a common planetary gear (PG) and an original CVT whose principle is directly inspired from a PG.

A. Planetary Gear Transmission

The kinematic diagram of a PG is given in Fig. 2 and the kinematic equation characterizing this well-known transmission is:

$$\frac{\omega_{pg,1} - \omega_{pg,4}}{\omega_{pg,3} - \omega_{pg,4}} = -\frac{R_{pg,3} R_{pg,2}}{R'_{pg,2} R_{pg,1}} \tag{1}$$

where $\omega_{pg,1}$, $\omega_{pg,3}$ and $\omega_{pg,4}$ are the angular velocities of the sun, the ring and the planet carrier, respectively, and $R_{pg,i}$ is the pitch radius of gear i.

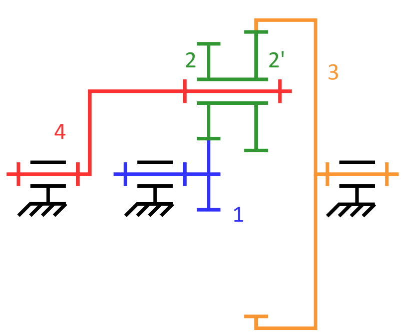


Fig. 2. Planetary Gear kinematic diagram. The different part of the planetary gear are called *sun* (1), *planets* (2, 2'), *ring* (3) and *planet carrier* (4).

B. Continuously Variable Transmission

The proposed CVT can be seen as a PG whose planets are inclined and cone-shaped to induce a ratio variation by moving the contact point on the cone surface. A kinematic diagram of this principle is illustrated in Fig. 3.

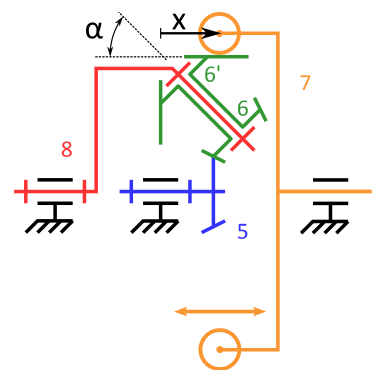


Fig. 3. Continuously Variable Transmission kinematic diagram. The sun is depicted in blue, the tilted planets in green, the carrier in red, and the ring in orange. This color code will be preserved throughout all the figures, including those presenting the prototype CAD

The key element of this new concept is the transmission between the ring and the planets. The planets on the ring side (6') are conical and their shafts are inclined so that the outer surface of the cones are tangent with a cylinder being concentric with the sun (5) and ring (7) axes. In this way, the ring can translate along its axis, while keeping contact with the cones, in order to vary the planet pitch radius $R'_{cvt,6}$ and therefore the transmission ratio.

Since the planet radius varies continuously, the motion cannot be transmitted with gears. Indeed, an integer number of teeth for each radius cannot be found. An alternative is thus to transmit the motion between the planets and the ring by friction.

It is moreover critical to minimize the energy required to change the ratio, and thus friction should be avoided for this movement. To achieve ratio changes by rolling instead of friction, we propose to build up the ring with several rollers whose axes are perpendicular to the ring axis and whose shape is such that they form a continuous circle of radius $R_{cvt,7}$ in contact with the planets, as illustrated in Fig. 4. In a way similar to the popular Swedish wheels being used in mobile robotics [20], the ring is thus blocked in the direction of motion transmission and free to rotate in the ring translation direction, i.e. the ratio changing direction.

Since the planets and sun axes are not parallel, the torque transmission between the planets (6) and sun (5) is achieved with bevel gears.

The kinematic equation linking the angular speed of the sun, the ring and the planet carrier is the same as for the PG:

$$\frac{\omega_{cvt,5} - \omega_{cvt,8}}{\omega_{cvt,7} - \omega_{cvt,8}} = -\frac{R_{cvt,7} R_{cvt,6}}{R'_{cvt,6} R_{cvt,5}} \tag{2}$$

but with $R'_{cvt,6}$ depending on the ring varying axial position x and the cone inclination angle α through :

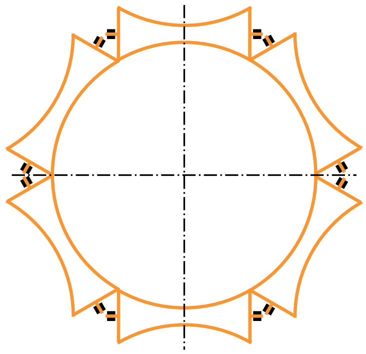


Fig. 4. Ring composed of several rollers whose axes are perpendicular to the ring axis

$$R'_{cvt,6} = x \sin\alpha \quad (3)$$

where $x = 0$ when the contact point is at the top of the cone.

C. Infinitely Variable Transmission

The CVT described in the previous section can be turned into an IVT by combining it with an inverted planetary gear, i.e. a PG whose ring is inside instead of being outside the planets, as illustrated in Fig. 5. The kinematic equation is exactly the same as for the classical PG, but opposite in sign:

$$\frac{\omega_{pg,1} - \omega_{pg,4}}{\omega_{pg,3} - \omega_{pg,4}} = \frac{R_{pg,3}R_{pg,2}}{R'_{pg,2}R_{pg,1}} \quad (4)$$

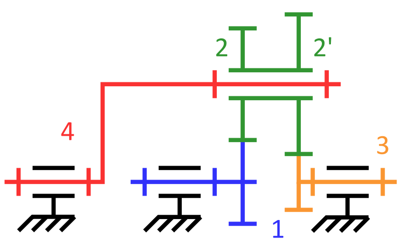


Fig. 5. Inverted Planetary Gear kinematic diagram

In order to obtain an IVT from the CVT and the inverted PG, the planet carrier of the CVT is connected to the ring of the PG (3) and the sun of the CVT to the sun of the PG, which is equivalent to imposing the following kinematic constraints:

$$\omega_{pg,1} = \omega_{cvt,5} \quad (5)$$
$$\omega_{pg,3} = \omega_{cvt,8} \quad (6)$$

In addition, the ring of the CVT is blocked in rotation, which is equivalent to imposing the kinematic constraint:

$$\omega_{cvt,7} = 0 \quad (7)$$

According to this configuration, the input and the output of the IVT correspond to the planet carriers of the CVT and of the PG, respectively. The kinematic diagram of this IVT is given in Fig. 6.

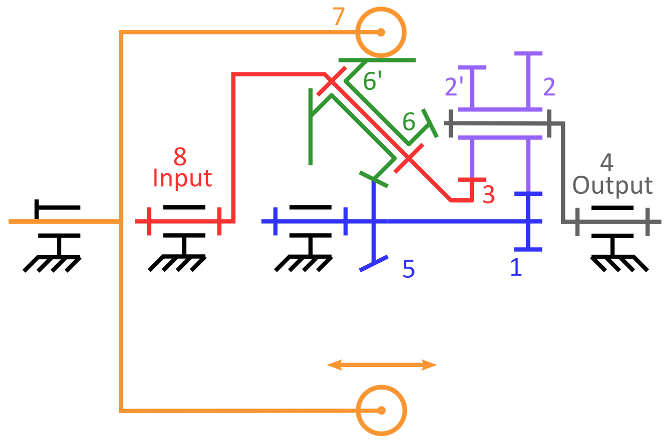


Fig. 6. IVT kinematic diagram. The suns are depicted in blue, the tilted conical planets in green, the CVT carrier and PG ring in red, the moving CVT ring in orange, the PG planets in purple and the PG carrier in dark grey. This color code will be preserved throughout all the figures, including those presenting the prototype CAD

From Eqs. 2 to 4, characterizing the CVT and the inverted PG, and Eqs. 5 to 7, corresponding to the kinematic constraints imposed to the CVT and the PG, the IVT variable transmission ratio τ_{ivt} can be derived as:

$$\tau_{ivt} = \frac{\omega_{pg,4}}{\omega_{cvt,8}} \quad (8)$$
$$= 1 + \frac{R_{cvt,7}R_{cvt,6}}{R_{cvt,5}\left(1 - \frac{R_{pg,3}R_{pg,2}}{R'_{pg,2}R_{pg,1}}\right)} \frac{1}{x \sin\alpha} \quad (9)$$

If $\frac{R_{pg,3}R_{pg,2}}{R'_{pg,2}R_{pg,1}} > 1$, the first term of Eq. 9 is negative. By increasing x from 0 to ∞, the IVT ratio can therefore vary from $-\infty$ to 1, i.e. including 0.

III. Prototype

A prototype was designed to implement the principle developed in Section II. This prototype has an outer diameter of 220 mm and is 150 mm long.

Fig. 7 shows a CAD drawing of the CVT ring, planets and sun. As previously mentioned, the rollers are diabolo-shaped so that their arrangement provides a continuous circle in the inner side of the ring. As a consequence, the contact point between the ring and the conical planets moves on this circle without discontinuity, while keeping a constant distance with respect to the center of rotation. In the presented design, the CVT has 4 cones and 6 rollers. With more cones, the number of contact points would increase and so would the maximum torque capacity. However, this reduces the size of the cones and then the range of ratio variations. This amount of cones offers an ideal force distribution within the mechanism while exploiting most of the volume being available. With 6 rollers, the contact points between the cones and rollers are also ideally distributed: at most two contact points can be located at the connexion between two adjacent rollers, while in this case the two other contact points will be located in the middle of both other rollers. This configuration maintains the capacity to transmit high torques all over the circumference, and minimizes the vibrations induced by a transition of the contact points from one roller to the next. This last condition is respected when the number of cones and the number of rollers are not multiples of each other. Note finally that the number of rollers must be strictly larger than the number of cones in order to prevent that two cones contact a single roller with different radius. This would induce large friction forces during ratio variation.

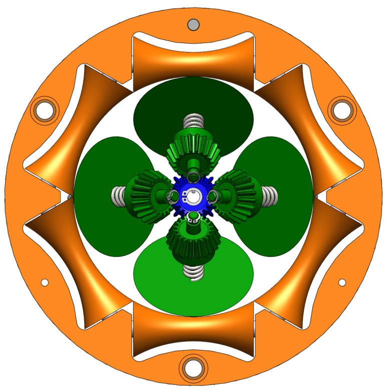


Fig. 7. IVT ring. The rollers are depicted in orange, the conical planets in green.

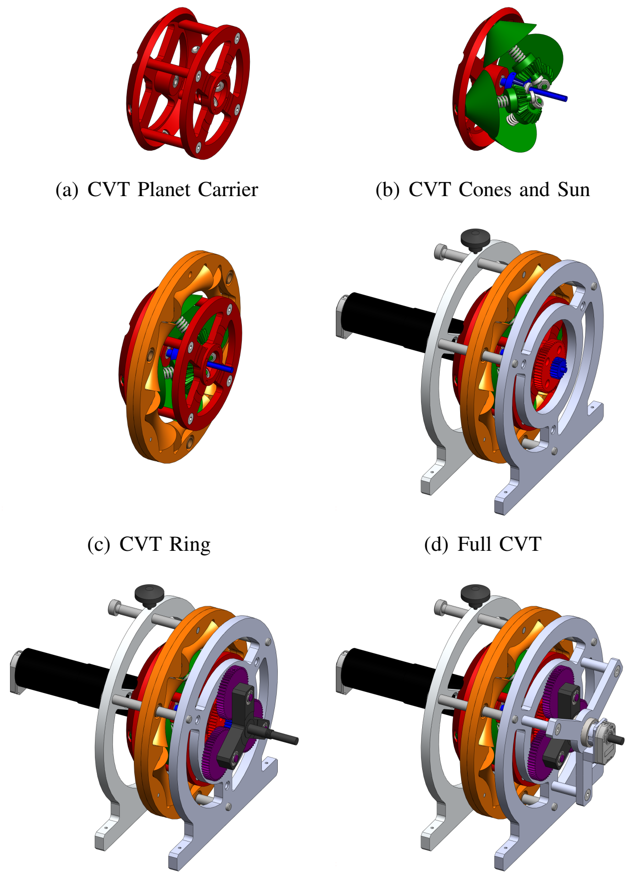
Fig. 8 shows CAD of the different components of the IVT and their assembly. The CVT planet carrier represented in Fig. 8(a) is a cage containing 8 bores being tilted by $\alpha = 45°$ to host the 8 bearings of the cones shafts. The planet carrier also hosts the bores for the sun bearings.

The cones are mounted on the shafts and free to translate along their axes. Fig. 8(b) shows the assembly. In order to minimize the contact force variations and guarantee an equal distribution of the force between the cones and the rollers, the cones are spring loaded. The torque is transmitted trough a key but the cone is not blocked along the axial degree of freedom as shown on Fig. 9, so that the springs can compress them on the rollers. The torque transmission between the planets and the sun is achieved by using 45° bevel gears.

The CVT ring is made up with the diabolo-shaped rollers mounted on their shafts through bearings. This allows changing the transmission ratio without recruiting friction forces, and thus with virtually no energy cost. The ring is displayed in Fig. 8(c). It is placed around the cones and is free to translate along the IVT longitudinal axis, thus modifying the instantaneous transmission ratio.

Fig. 8(d) shows the assembled CVT with an external frame and a motor to actuate the mechanism. The ring is mounted on 3 shafts through linear bearings. It is free to translate along the shaft direction but is blocked in rotation. Two gears are placed at the CVT output. One is connected to the planet carrier - i.e. the CVT input - and the second is connected to the sun - i.e. the CVT output.

Fig. 8(e) shows the planetary gear being connected to the two output gears of the CVT. The output of the IVT is made up with the planet carrier being placed around the two output CVT gears.



(a) CVT Planet Carrier (b) CVT Cones and Sun

(c) CVT Ring (d) Full CVT

(e) IVT Planetary Gear (f) Full IVT

Fig. 8. Sequential assembly of the IVT CAD, highlighting the different components.

Fig. 8(f) shows the complete IVT and Fig. 9 shows a cut view of the IVT. This figures better emphasizes how all the components are connected and geared to each other. The figure highlights that the cones must be spring loaded and how planets are geared with the sun through tilted bevel gears.

We further manufactured a prototype of this design. It is showed in Fig. 10.

The geometrical parameters of the actual prototype are the following:

- CVT ring radius: $R_7 = 70\,\text{mm}$
- Cone angle: $\alpha = 45°$
- Ring range: $x \in [21; 47]\,\text{mm}$
- Bevel gears have a ratio equal to 1, i.e. $R_6 = R_5$
- Planetary gears radii: $R_1 = 10\,\text{mm}$, $R_3 = 27\,\text{mm}$, $R_2' = 15\,\text{mm}$ and $R_2 = 22\,\text{mm}$

Introducing these values in Eq. 9 above, the IVT ratio varies within the range $\tau_{ivt} \in [-0.58; 0.23]$, thus spanning across negative to positive values.

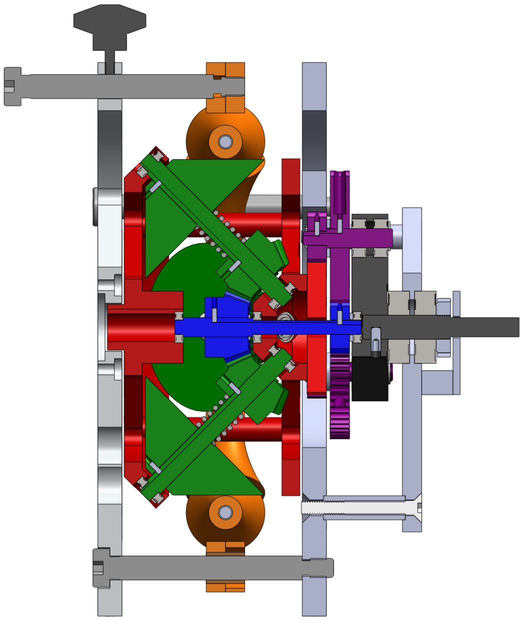


Fig. 9. IVT cut view

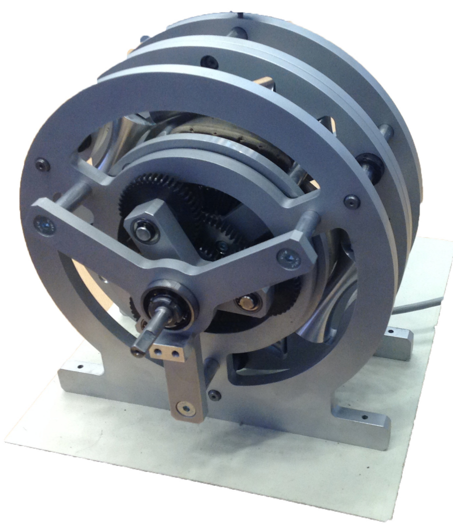


Fig. 10. Picture of the actual IVT prototype

IV. Experimental Validations

A preliminary experiment with the prototype was carried out. This experiment aims at validating the IVT working principle, i.e. to show that the output velocity can indeed vary from negative to positive values while maintaining a constant input velocity. The CVT ring is moved on its whole range and the actual ratio is compared with the predicted one, provided by Eq. 9. A constant input velocity was provided with the motor at the input side and the output velocity was measured for different positions of the ring. In this experiment, the output was not connected to any load and the CVT ring was moved by hand.

Fig. 11 shows that the IVT ratio indeed changes when the ring is moved. The input velocity was controlled to be constant (around 11 rad/s) while the output velocity varied from -3.1 to 6.4 rad/s. Fig. 12 shows the measured ratio and the expected one. This experiment was video-taped and the recording is provided as supplemental multimedia attachment. The video further validates another very important feature of our design, namely that the transmission ratio can be changed when the input is at rest (zero velocity). The static force needed to move the ring has been measured with a force gauge and it never exceeds 1 N.

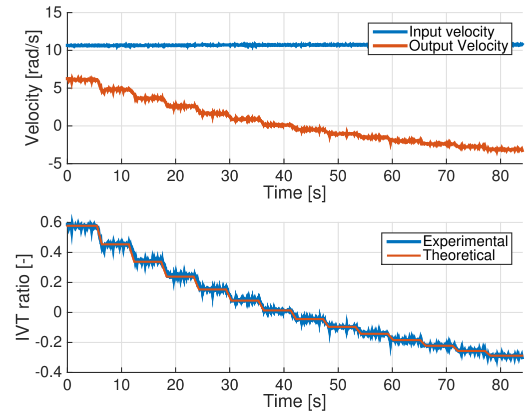


Fig. 11. Input and Output IVT velocities during manual changes of the ring position. The theoretical value is obtained from Eq. 9.

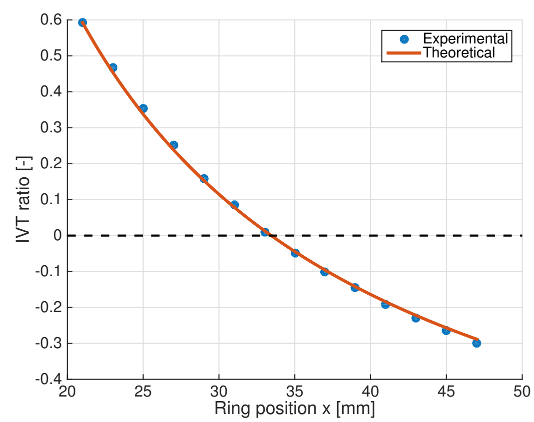


Fig. 12. IVT ratio variation as a function of the ring position. The theoretical value is obtained from Eq. 9.

V. Conclusion

This paper presented a new kind of Infinitely Variable Transmission. The transmission ratio of this IVT can be changed even when the mechanism is at rest, theoretically with no frictional forces. This mechanism is thus an ideal candidate for applications in legged robotics (humanoids and prosthetics). These applications indeed require joints providing largely fluctuating output power, but which should be ideally fed by motors working close their optimal constant power.

The design of the IVT is the combination of a CVT and a planetary gear. The CVT is a modified planetary gear where the planets are turned into tilted cones. The ring is made up with rollers and can translate along the cones in order to change the contact point radius and then the transmission ratio.

A preliminary experiment was realized on a prototype. This experiment showed that the transmission output can indeed continuously vary from negative values to positive values with a constant input velocity. This experiment thus validated the IVT principle and showed that the measured ratio corresponded to the predictions.

Future steps will focus on improving the prototype, mainly regarding its mechanical efficiency. Bevel gears, which are noisy and inefficient, should be replaced by friction gears to transmit the torque between the planets and sun of the CVT. Then, the spring loading would have a positive effect on both sides of the tilted planets. Secondly, we aim at increasing the torque transmission capacity between the cones and rollers. We are currently exploring the use of traction fluids to reach this goal [21].

Finally, future prototypes will be designed with a smaller size, so as to be integrateable into a lower limb prosthesis. Particular attention will be paid to maximize the energy efficiency of the second prototype. Indeed, this is a necessary condition to turn this concept into a viable solution for a highly energy efficient artificial legs.

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