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New Three DOF Ankle Mechanism for Humanoid Robotic Application: Modeling, Design and Realization

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Abstract—**Designing and control of biped robot are still open questions. Design of ankle joint which is considered one of the more compact with high power capacity and low weight is a big challenge. The very important role played by this joint during walking, makes its design and control the first step of having a robust walking biped. In this paper, a novel three dof hybrid mechanisms has been proposed. This mechanism is actuated hydraulically and uses cable technology for power transmission. The proposed solution fulfils the requirements induced by both geometrical and biomechanical constraints. At first, the geometrical and kinematics properties of the proposed solution have been developed. A simulation tool has been built using ADAMS software and used to carry out early design dimensioning of the several components. Singularity study is detailed showing the advantage of this new solution. Control method has been proposed and tested. Finally manufactured prototype of this solution is presented with preliminary results showing the performances of the mechanism. This mechanism is a part of an International patent accepted at INPI- France.**

I. INTRODUCTION

ANKLE joints is one of the more critical joints for the biped robots. This joint has to develop a high torque in very small space inducing an increase of torque to size ratio. With three degree of movement in the human being, this joint plays a very important role during the walk. In the last year many active humanoid robots have been built, such as HRP2 [1], Qrio [2], H7 [3],Wabian2 [4], Lola[5] and ROBIAN [6]. For these entire robots, there are always two global questions to answer concerning the ankle joint. First of all, how many degrees of freedom can exist in the ankle? Then which actuation technology has to be used? It is clear that with any given answer the available size to include this joint remains the big challenge of this problem. Indeed, all the existing humanoid robots cited above have ankles, which “blow up” due to the transmission mechanism based on the harmonic drive device. To actuate ankle joint, all the above listed robots use electric motor technology, which is low cost technology and not so difficult to control. But in the other hand, as the ankle joint needs high torque at low speed; high gear box ratio is required. Consequently, this increases the mechanical parts number and leads to quasi rigid connection between actuator and joint axis. Furthermore, the available volume constraint is not respected leading to the inflation mentioned above.

Other robots are using hydraulic technology for actuation such as DB, CB built by Sacros company [7]. The big advantage of this technology is producing the power in the meaning of high torque directly, which reduces mechanical parts number, and allow the designer to respect human appearance constraints. Of course the drawback of this solution is linked to the central hydraulic group; with its pipes passing through all the joints to arrive to the ankle one.

Based on the pervious analysis, a novel hydraulic actuating technology was proposed by Alfayad et al [8], This solution allows us to actuate the ankle, with merging the advantages of both electric and classic hydraulic technologies.

The other point take into account, when thinking about ankle joint, is linked to the number of degrees of freedom (dof), which must be integrated in the ankle. Clearly an ankle with three dof is very useful during the walk and gives more chance to produce human like walk. But building this three dof joint come in contradiction with the available volume constraints. The most existing robots in the world have ankle with two dof. So, our challenge with the new proposed solution concerns the achievement of three dof with respecting the volume constraints.

On the kinematic point of view, the most known ankle joint as those of HRP2 [1], H7 [3], and ROBIAN [6] are built with serial mechanisms. This induces the drawback that the actuator of the first joint must support the weight of the second actuator. On the other hand parallel mechanism can be used. In this kind of structure, the load will be equivalent between the different actuators. But locating all the actuator on the base of the parallel mechanism will increase the dimensions of this base. It is also well known that the control models of the parallel mechanisms are more complex then serial ones. The

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proposed mechanism tries to merge the advantages of serial and parallel structure, in a hybrid one. This allow us to reorganize serial and parallel parts together in such way to respect the size constraints, not overload the actuators, and produce the three dof motion with easy control models. This paper presents our recent research concerning the development of three dof hybrid mechanism actuated hydraulically and used for the ankle of our underdevelopment humanoid robot called HYDROïD. The paper is divided in five sections. In the next section the geometrical, masses, joint ranges, torques, and speed constraints, which must to be satisfied by the proposed ankle joint solution, are given. In the third section, the kinematic analysis of the proposed mechanism is achieved. Then its kinematics properties and singularity problem study are developed. In the fourth section, Adams software based simulation tool used for early stage dimensioning of the proposed mechanism is presented. The control loop used for the system is detailed. Simulation results showing many interesting properties of the system are presented. Finally in the fifth section the mechanical structure of the proposed solution is given. Then the real prototype mechanism fabricated for HYDROïD robot is presented with preliminary experimental results. At the end conclusion and further developments of this work are listed.

II. MAIN CONSTRAINTS FOR ANKLE JOINT DESIGN

A. Geometrical constraints:

To insure human appearance, and to facilities communication between human and robots, a size of $1.6m$ and a mass of $50kg$ have been chosen for our HYDROïD humanoid robot. To define mass, inertia, and geometrical constraints, Hanavan modified model has been used [9]. The inputs of this model are the height and the total mass of the robot, while the outputs are all the masses, inertia, dimensions, gravity center position, and the approximated geometrical form, for all the subparts of the humanoid robot. Based on this model, the foot is presented as parallelepiped, and the shin with shortened cone (See Fig.1). Table 1 presents the available space for the ankle (length and radius dimensions) and mass of ankle joint.

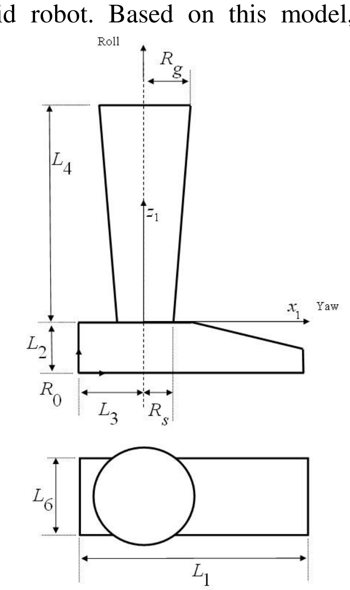

Fig.1.Available size to locate the ankle mechanism.

TABLE I
ANKEL JOINT AVALABLE DIMENSIONS & MASS

Symbol	Quantity	Values
L1	Foot long	24,3 Cm
L2	Foot wide	8 Cm
L3	Foot height	6,24 Cm
L4	Distance between foot back and ankle joint centre	7,2 Cm
L5	Shin height	3,92 Cm
Rs	Shin small radius	2,94 Cm
Rb	Shin big radius	46,7 Cm
mf	Foot mass	0,8 Kg
mt	Shin mass	1,9 Kg

Based on physical aspects and as mentioned by Abba et al [10], the more the shin center of gravity is closer to knee, the least power is needed to realize the walk. The proposed solution will try to locate the center of gravity as nearest as possible to the knee as will detailed in the next section.

B. Motion range, speed and torque constraints:

In another hand, the ankle joint range values have been chosen to realize a normal human walk at speed of $1.2m/s$. Based on biomechanical analysis [11], [12], this joint has a range of $-10^\circ + 30^\circ$ in the pitch direction, while it has $\pm 10^\circ$ in the roll and yaw direction. Furthermore, the maximum speed around the pitch axis is estimated to $4.3rad/s$ to achieve the desired walking speed.

To determine the needed torque during the walk, biomechanical studies, based on inverse dynamic models, could be analyzed [11], [12]. Nevertheless, a quasi-static equilibrium of the worst case based on concentrate mass model is sufficient to have a first estimation of the torque. As shown in Fig2, the total mass of the robot is concentrated in its center of gravity. In this case, the ankle must be able to keep the projection of the center of gravity in contact surface defined by the foot. Using the data listed in

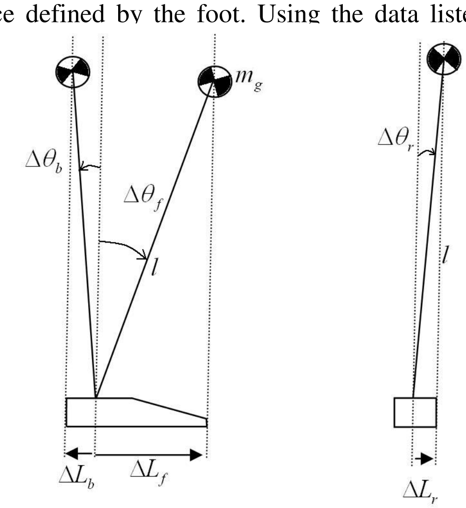

Fig.2.Mass concentrated model.

Table1, the ankle joint must satisfy a torque of almost $85Nm$ in the pitch direction, about $20Nm$ in the two other directions.

III. NEW HYBRID ANKLE JOINT KINEMATIC ANALYSIS

Our aim is to build a simulation tool of the new mechanism, which will enable us to carry out the earlier stage dimensioning process. To do so, it is necessary to achieve both geometrical and kinematic model of the proposed solution. These two models have to be established once the kinematic structure is chosen. Based on the constraints listed above, a type synthesis process is carried out and on kinematic solution is identified. This choice is motivated in the following paragraph.

A. Kinematic structure:

Once all the constraints for ankle joints are listed, the proposed mechanism can be detailed. To built spherical ankle joint, three rotation joint with intersecting axes must be built. As shown in Fig.1, the ankle joint center is located at point, which its coordinates in (x_0, z_0) plane are (L_2, L_3). This means that the intersection of the three axes of the ankle joint must be at this point. Theoretically, the axes of these three rotation joints, can take any direction. Nevertheless, to minimize coupling between the three joints and to reduce maximum range movement in each axis, the rotation joint axes direction are chosen to be in parallel to the roll, yaw, pitch directions at initial position (See Fig.1).

At this point, the challenge is to locate three rotation joints, with intersection at ankle joint point, and parallel to roll, yaw, and pitch directions, while respecting the available size constraints. By analyzing Fig.1, the available volume to locate the mechanism is the shortened cone with dimensions (L_4, R_s, R_b). Decision was taken to not use the available size of the foot, to locate the mechanism. This was motivated by three considerations. At first, the foot should be a movable part of the mechanism. Secondly, mechanism center of gravity should be as near as possible to the knee according to Abba et al [10] study listed above. Finally, in order to integrate contact sensor inside the foot, enough space is needed to be kept. On the other hand, locating the ankle joint in the truncated cone, means locating actuators, joints axes, transmission power mechanism (between actuators and joints axes), and finally all necessary sensors, in this available space. This constitutes obviously a big challenge.

The first joint to be located is the vertical one (in the z_1 direction (See Fig.1). This joint can be located at any point of the vertical axis. To make sure that the whole mechanism center of gravity is closer to the knee joint, the position of this first joint was chosen to be at the top of the shortened cone. The directions of the second and third rotation joints are respectively x_1 and y_1. Due to their weight, the actuators have to be located at the highest level in the truncated cone. This will lead to let sufficient space to locate the joint axes at the ankle joint center. Such solution will participate to bring the gravity center of the total mechanism closer to the knee joint. Of course mechanical part will be necessary to transmit power between actuators and the joint axes. Furthermore, as these two rotations joints have limited angular movement, without complete circular rotation needed, cable transmission mechanism was chosen. Cables have low mass and high flexible properties, which are very useful in this application [13]. On the other hand, due to the fact that cables can only pull (and not push), two cables are needed for each rotation joint. Furthermore, as enough space is available in the vertical direction, linear actuators placed in parallel vertically will be a smart solution leading to slim ankle joint. Fig.3 presents simplified sketch of the proposed mechanism. All the main mechanical parts are located near to knee joint.

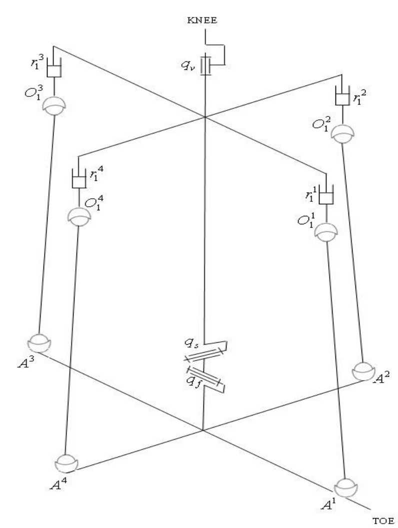

Fig.3.Sketch model of the new mechanism.

As mentioned previously, actuating ankle joint hydraulically gives the possibility to produce a natural compliant motion CB[7]. Supplying the power forward in torque way decreases also the mechanical parts number. On the other hand, using the new hydraulic actuating system, based on Hydraulic Energy Converters (HEC) developed by (Alfayad et al) [8], will minimize the drawbacks of the classic hydraulic actuator. Each joint will have its own "micropump" insuring independent pressure production (for each) in compliance with the real needs. Three HEC will be included in the calf to actuate in one side the ankle pitch and yaw motions and in the other side the active toes which equip

HYDROïD humanoid robot.

B. Inverse Geometrical Model:

To determine the numerical values of the geometrical variables, Inverse Geometrical Model (IGM) is needed. This will allow us to calculate the maximum range of the linear actuators required to achieve the motion range in all direction. To do this, a kinematic structure of the mechanism detailing the choices made above, has been proposed (See Fig.4). As the used cables have relatively small length, a first approximation was taken in consideration by modeling the cable as two spherical joint separated by rigid body.

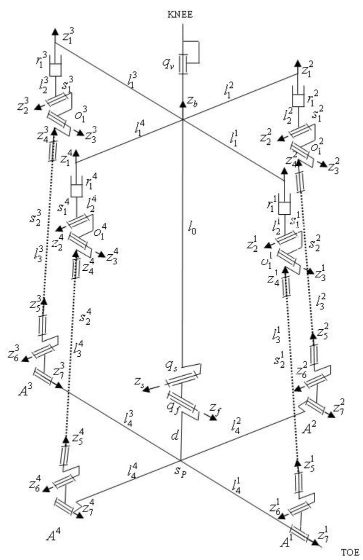

Fig.4.Kinematic model of the mechanism.

To carry out the IGM, several notation where adopted. The j^{th} closed kinematic chain is designated by chain $Loop_j$ for $j = 1,2,3,4$. The mechanism outputs are grouped in a vector $q = (q_s, q_f, q_v)$. These angles will be measured thanks to avalible sensors (see Mechanical Design pargarph). The mechanism inputs are the linear joints positions named r_1^j for $j = 1,2,3,4$. The rotation of the i^{th} joint in the j^{th} closed loop is designated by θ_i^j . r_1^j, q_v are the active variables while all the remaining joints are passive ones. Infact and due the cables these variables are grouped into two sets $\{r_1^1, r_1^3\}$ and $\{r_1^2, r_1^4\}$ giving the real joint

To establish the IGM, the equivalent open mechanism obtained by braking the z_5^j joints (See Fig.4) is taken into acount. Forward geometrical models were developed for this equivalant open mechanism. Finally the IGM can be presented as following:

For $Loop_1$ and $Loop_3$:

$$\theta_3^j = \sin^{-1}\left(\frac{d.S_{qv}}{l_3^j}\right)$$

$$\theta_2^j = \sin^{-1}\left(\frac{d.S_{qs}.C_{qf} + l_4^j.C_{qs} - l_1^j}{l_3^j.C_3^j}\right)$$

Then the active variables of these two loops can be written as:

$$r_1^j = l_0 - l_2^j - l_4^j.S_{qs} + d.C_{qs}C_{qf} - l_3^j C_2^j C_3^j \tag{1}$$

Where $S_\alpha = \sin(\alpha)$ and $C_\alpha = \cos(\alpha)$. The several lengths are defined on Fig.4. On the other hand, for $Loop_2$ and $Loop_4$, the same relations can be established:

$$\theta_3^j = \sin^{-1}\left(\frac{d.S_{qv} + l_4^j.C_{qf} - l_1^j}{l_3^j}\right)$$

$$\theta_2^j = \sin^{-1}\left(\frac{d.S_{qs}.C_{qf} - l_4^j.S_{qs}.S_{qf}}{l_3^j.C_3^j}\right)$$

This leads in the same way to the following expression of the active joint variables:

$$r_1^j = l_0 - l_2^j - l_4^j.C_{qs}.S_{qf} + d.C_{qs}C_{qf} - l_3^j C_2^j C_3^j \tag{2}$$

C. Kinematic Models:

The aim in this paragraph is to establish the relation between the global kinematics variables given by vector $\dot{X} = (\dot{\theta}_r, \dot{\theta}_y, \dot{\theta}_p)$ and active ones grouped in vector $\dot{r} = (\dot{r}_1, \dot{r}_1^1, \dot{r}_1^2, \dot{r}_1^3, \dot{r}_1^4, \dot{q}_v)$.

Where $\dot{\theta}_r$, $\dot{\theta}_y$ and $\dot{\theta}_p$ are the angular velocity in the roll yaw and pitch directions respectively.

Using the kinematic composition formula, the kinematics of the j^{th} closed loop can be descibed as following:

$$Tc_{Sp/Sb} = Tc_{S1/Sb}^j + Tc_{S2/S1}^j + Tc_{SP/S2}^j \tag{3}$$

Where $Tc_{sp/sb}$: is the kinematic wrench of the foot relative to the base of the parallel mechanism.

$Tc_{S1/Sb}^j$ is the kinematic wrench of the j^{th} linear actuator relative to the base of the parallel mechanism.

$Tc_{S2/S1}^j$ is the kinematic wrench of the j^{th} cable relative to j^{th} linear actuator.

$Tc_{SP/S2}^j$ is the kinematic wrench of the foot relative to j^{th} cable.

This relation expressed with the individual screws [14] as follows:

$$Tc_{Sp/Sb} = \dot{r}_1^j \$_1^j + \dot{\theta}_2^j \$_2^j + \dot{\theta}_3^j \$_3^j + \dot{\theta}_4^j \$_4^j + \dot{\theta}_5^j \$_5^j + \dot{\theta}_6^j \$_6^j + \dot{\theta}_7^j \$_7^j \quad (4)$$

Where $\dot{\theta}_i^j$ is the derivative of the θ_i^j and $\$_k^j$: is the kinematic screw of the k^{th} joint in the j^{th} closed chain.

As r_1^j is the active variables in the closed chain, we can define the reciprocal screw of this variable, named $\$_1^{R_j}$, which satisfies:

$$\$_i^j \$_1^{Rj} = 0, i = 2,3,4,5,6,7 \quad (5)$$

The frame R_1^j placed on O_1^j and parallel to R_b is chosen to be the working reference frame for each closed chain. The j^{th} cable projected in this frame can be written with its coordinates as:

$$A^j O_1^j = \begin{bmatrix} U_j & V_j & W_j \end{bmatrix}_{R_1^j}$$

Hence, the solution of the set of equations (5) can be established which gives the desired screw $\$_1^{R_j}$:

$$\$_1^{Rj} = \frac{1}{\sqrt{U_j^2 + V_j^2 + W_j^2}} \begin{bmatrix} U_j & V_j & W_j & 0 & 0 & 0 \end{bmatrix} \quad (6)$$

By multiplying Eq.(4) by this solution, and by choosing A^j (See Fig.4) as working point for the j^{th} closed chain, the following relation can be used:

$$\$_1^{R_j} Tc_{Sp/Sb}(A^j) = \dot{r}_1^j \$_1^j \$_1^{R_j} \quad (7)$$

As the kinematic wrench of foot relative to the base s_b, projected on R_b can be written as:

$$Tc_{Sp/Sb}(A_0) = \dot{q}_s Z_s + \dot{q}_f Z_f = \begin{vmatrix} \dot{q}_f C_{qs} & -\dot{q}_s & \dot{q}_f S_{qs} \end{vmatrix} \quad (8)$$

Then based on the advantage that the hybrid structure, has its first rotation joint (q_v) independent of the two others joints (q_s, q_f) and by replacing Eq.(6), Eq.(8) in Eq. (7), for all the four closed loop, the kinematic model can be expressed as:

$$\begin{bmatrix} L_4^1 W^1 & L_4^1 S_{qs} V^1 & 0 \\ 0 & L_4^2 (C_{qs} W^2 - S_{qs} U^2) & 0 \\ -L_4^3 W^3 & -L_4^3 S_{qs} V^3 & 0 \\ 0 & L_4^4 (C_{qs} W^4 - S_{qs} U^4) & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} \dot{q}_s \\ \dot{q}_f \\ \dot{q}_v \end{bmatrix} =$$

$$\begin{bmatrix} W^1 & & & & 0 \\ & W^2 & & & \\ & & W^3 & & \\ & & & W^4 & \\ 0 & & & & 1 \end{bmatrix} \begin{bmatrix} \dot{r}_1^1 \\ \dot{r}_1^2 \\ \dot{r}_1^3 \\ \dot{r}_1^4 \\ \dot{q}_v \end{bmatrix} \quad (9)$$

Equation 9 has the following classical matrix formulation:

$$A \cdot \dot{q} = B \cdot \dot{r} \quad (10)$$

On the other hand, the global kinematic variable $\dot{X}$, defined previously, can be written as:

$$\dot{X} = \dot{q}_s Z_b + \dot{q}_v Z_v + \dot{q}_f Z_f = \begin{bmatrix} \dot{q}_s S_{qv} + \dot{q}_f C_{qv} C_{qs} \\ -\dot{q}_s C_{qv} + \dot{q}_f S_{qv} C_{qs} \\ \dot{q}_v + \dot{q}_f S_{qs} \end{bmatrix}$$

$$= \begin{bmatrix} 0 & C_{qv} C_{qs} & S_{qv} \\ 0 & S_{qv} C_{qs} & -C_{qv} \\ 1 & S_{qs} & 0 \end{bmatrix} \begin{bmatrix} \dot{q}_v \\ \dot{q}_f \\ \dot{q}_s \end{bmatrix}$$

(11)

This can be reformulated as:

$$\dot{X} = D.\dot{q} \quad (12)$$

Furthermore, based on Eq.(10) and Eq.(12), the kinematic model of the proposed ankle mechanism can be finally established as:

$$A \cdot D^{-1} \cdot \dot{X} = B \cdot \dot{r} \quad (13)$$

D.Singularity analyzing:

The first use of the established kinematic models achieved above can be the singularities analysis. Indeed, the final design of the mechanism should take into account these important aspects, which affect the performances of the system. Analyzing the D, A, B matrices, leads to identify that the determinant of D matrix can be expressed as:

$$\det(D) = -\cos(q_s) \quad (14)$$

So the first singularity occurs for $q_s = \pm\pi/2$.

On the other hand, based on symmetrical considerations adopted for the HYDROïD robot ankle (See table2). The singularity of matrices A, B can be studied for $j = 1,2$. Hence, we can establish the following expressions for A and B matrices:

$$\det(A[1..2,1..2]) = L_4^1 L_4^2 L_3^2 C_2^1 C_3^1 C_3^2 C_{qs-\theta_2^2} \qquad (15)$$

$$\det(B[1..2,1..2]) = L_3^1 L_3^3 C_2^1 C_3^1 C_2^2 C_3^2 \qquad (16)$$

Based on the IGM developed in the previous paragraph, the zeros of the Eq.(15) and Eq.(16) are calculated. This leads to identify the second singularity for $q_f = \pm\pi/2$. This singularity study shows the conditions for the proposed mechanism, to work far away from the singularity positions.

IV. SIMULATION TOOL AND RESULTS

A. Simulation tool

Based on the established IGM and kinematic models established in the previous section, virtual model has been built using ADAMS, (see Fig5). Real mass, inertia, dimensions of HYDROïD, have to be integrated in the simulation tool. On the other hand, based on biomechanical data obtained by analyzing human walk at speed $1.2m/s$ and using motion capture system, effort applied by the ground on the feet during walking gait has been calculated. These effort components were integrated on the virtual model to simulate the natural walk environment for the ankle.

To let the proposed ankle mechanism following the desired motion, a control loop based on the inverse geometrical and kinematic models, and using PID, has been built (See Fig.6). The inputs of this control loop are the desired ankle angles $X_d = (\theta_R, \theta_Y, \theta_P)$.

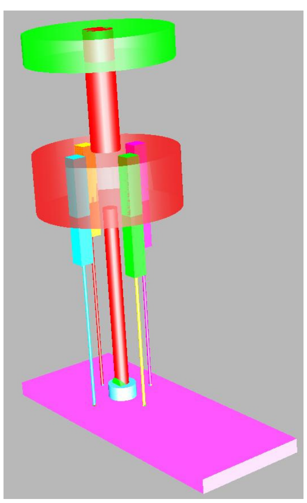

Fig.5.Ankle virtual model.

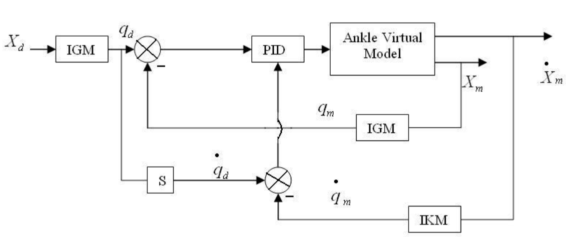

Fig.7. Used control loop.

B. Simulation results

i) Variables lengths and active joint ranges: The first result concerns the determination of the variable lengths of the proposed mechanism. We should notice the fact that, for constant pressure value, increasing the l_4^j variable (See Fig.4) values will increase produced torque at the ankle joint. The variables l_4^j are chosen to have the biggest value in the available volume. On the other hand, once a nominal pressure value is chosen, the active pistons surface needed for insuring the nominal torque is calculated. As the shin is modeled as truncated cone, determining the active piston surface will lead us to determine the level where this piston has to be located to satisfy shin geometrical constraints. The numerical obtained values for HYDROïD robot are shown in table 2.

Once the IGM has been developed, and the numerical values are chosen, the maximum variation of the linear actuator r_1^j, can be calculated. To ensure the satisfaction of the geometrical constraints in the vertical directions, $r_1^j(q_s, q_f) : j = 1,2,3,4$ were calculated for all posible values of (q_s, q_f). This leads to the following ranges: $r_1^1 \in [-15,+5].mm$ while $r_1^2 \in [-5,+5].mm$. These small needed values show another advatage of the proposed solution.

ii) Joint positions, efforts and needed torques: Fig.8 shows the ankle pitch angle achieved by the PID controller during the simulation of walking gait. The desired and the measured (with Adams) values are both plotted on Fig.8.

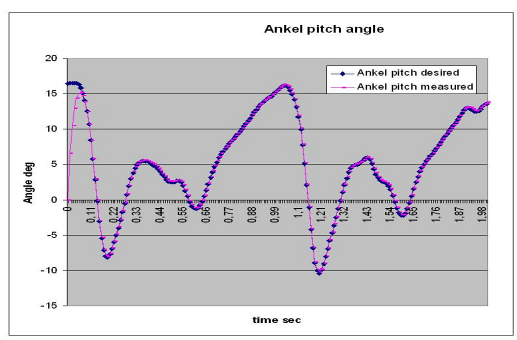

Fig.8 Aankle pitch angle command.

Another aspect, which is important in early stage dimensioning process, concerns the forces in the joints. These forces fix the geometrical and the material properties that should be chosen for the final prototype. Fig. 9 gives the magnitude of the force at the level of the spherical joint located at O_1^1 as an example of this kind of joint force unknown.

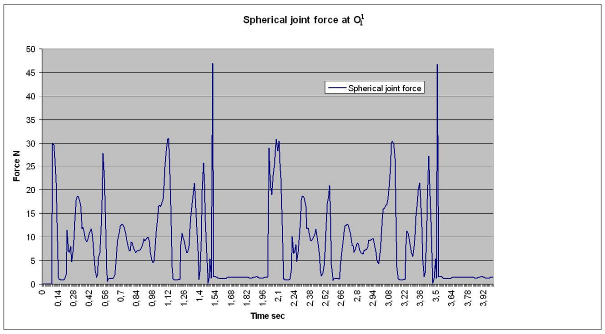

Fig.9.Spherical joint force.

Finally, it is important to determine the total force needed for the active joints. This will fix the nominal pressure to be used for the pistons. Fig.10 gives the required forces for linear actuators $\{r_1^1, r_1^3\}$ during walking cycle. The movement concerns the flexion/extension of the ankle joint submitted to the foot force reaction.

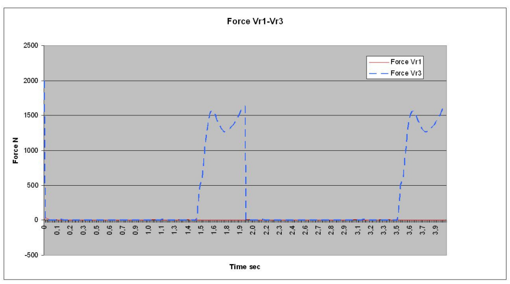

Fig.10.Required force in linear actuators.

V. MECHANICAL DESIGN OF THE PROTOTYPE

A. Mechanical design:

Once, the different simulation stages were carried out and based on all the previous analysis, the proposed new mechanism shown in Fig.3 and Fig.4 was designed. Fig.11 gives in detail 3D drawing of the proposed solution. As G1 is the knee base part, the first rotation joint q_v is directly activated with an integrated rotational hydraulic motor. Ch1, Ch2, and Ch4 present the fixed parts of this hydraulic rotary motor while Ch3 and Ch6 form its rotator. To achieve rotation joint axes in the pitch and yaw directions, crossed shaft Ch16 has been integrated at the ankle joint center. This shaft rotates between two supports Ch18 and Ch15, which are fixed with foot base Ch20. To actuate rotation joint in the pitch direction, two linear pistons (Ch10, Ch11) are integrated in the roll, yaw plane. These pistons are connected with two flexible cables. The second end of the left cable is connected with the right support Ch15, while the other end of the right cable is connected to the left support Ch8. A pulley Ch19 with two integrated paths has been fixed on the foot base. This allows the two cables following the pulley paths while they change their direction of $\pi/2$ to go to the supports.

The same system has been built in the yaw direction. At this time, the two ends of the cables are connected directly on the foot base. As shown on Fig.4, in the aim of minimizing the cable deformation and the coupling between pitch and yaw cables, the cables pass through the shaft Ch16. A plastic ring Ch21 with a circular inner section has been inserted in the shaft.

Spacers Ch7 has been used to provide space needed to locate the three HEC, responsible of producing hydraulic power for ankle and toes joints as mentioned before. Thanks to a central hole through all the mechanism, this design is completely compatible with classic hydraulic actuation technique. Any hydraulic pipes or electric cables for power and sensor can pass through this hole.

Finally, to measure the joint positions of this mechanism, three tiny potentiometers have been integrated directly at the joints rotation axes.

B. Prototype and preliminary tests

A global view of the ankle prototype is given in Fig. 12. The two ankles are already manufactured and

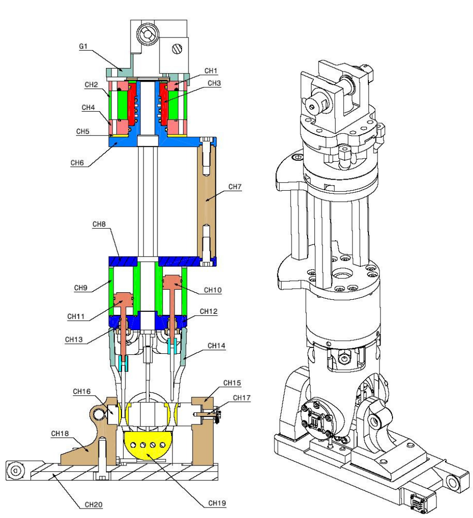

Fig.11. 3D CAD details of the proposed mechanism

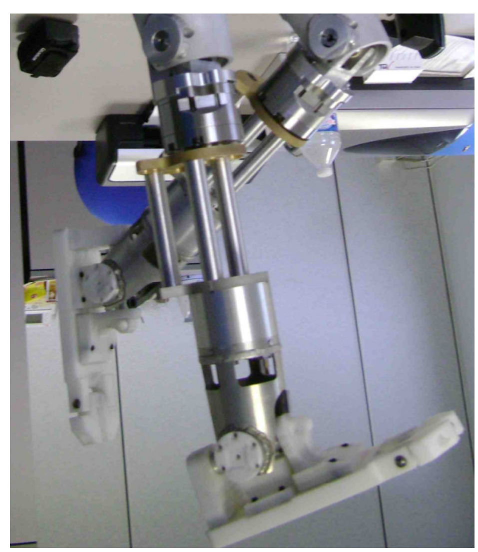

Fig.12. Ankle prototype for HYDROïD

assembled on the HYDROID humanoid robot. Preliminary tests were carried out in order to show the performances. These experimental results are included in the attached video file.

VI. Conclusion

In this paper, a new hybrid mechanism for ankle application was developed. The big challenge in the field of the design of humanoid robot is related to the performances in terms of torque and speed. Usual solutions with two dof mechanisms are based on serial kinematic structure actuated with electric motors. In this case, to produce the required torque and speed, high transmission ratio gearbox (i.e. Harmonic drive) is needed. This leads to "blow up" of the ankles. The new solution proposed in this paper avoids these drawbacks since it is based on hybrid solution. Very compact solution with three dof mechanism achieving roll, pitch and yaw motion is proposed. This leads to smart and slim ankle. The mechanism was designed according to geometrical and kinematic constraints. A cable transmission mechanism transmission was adopted in order to locate the actuator along the shin main axis. The proposed solution can be either actuated with the HEC component or with hydraulic group center. The proposed solution is a part of international patent registered at INPI-France. A simulation tool based on Adams was developed and used in order to carry out the early stage dimensioning process. The geometrical and kinematic models were established according to screw theory and used in simulation process to analyze the dynamic behavior of the mechanism during walking gait. A prototype was designed and manufactured. This ankle mechanism is a part of our under development HYDROïD robot. The preliminary experimental results were carried out showing the efficiency of the proposed solution. The further work concerns the foregoing stage in control of this mechanism with HEC during the achievement of HYDROïD first steps.

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References

[1] K. Kaneko, F. Kanehiro, S. Kajita, H. Hirukawa, T. Kawasaki, M; Hirata, K. Akachi, and T. Isozumi, «Humanoid robot HRP-2,» in Proc. IEEE Int. Conf. Rob. Aut. (ICRA), NewOrleans, USA, 2004, pp. 1083-1090.

[2] http://www.kitt.net/blog/gadget/2005/01/sony-qiro-biped-robot.html

[3] K. Nishiwaki, S. Kagami, J. Kuffner, M. Inaba, and H. Inoue, «Humanoid «JSK-H7»: Research platform for autonomous behavior and whole body motion,» in Proc. Int. Workshop Humanoid and human friendly robotics (IARP), Tsukuba, Japan, 2002, pp. 2-9.

[4] Yu Ogura, Hiroyuki Aikawa, Kazushi, Shimomura, Hideki Kondo, and Akitoshi Morishima, Hun-ok Lim Atsuo Takanishi, "Development of a New Humanoid Robot WABIAN-2", Proc. of IEEE ICRA 2006, pp 76-81,Orlando, Florida

[5] S. Lohmeier, T. Buschmann, H. Ulbrich, F. Pfeiffer, "Modular Joint Design for Performance Enhanced Humanoid Robot LOLA", Proc. Of IEEE ICRA 2006, pp 88-93, Orlando, Florida.

[6] A. Konno, R. Sellaouti, F. B. Amar and F. B. Ouezdou, «Design and Development of the Biped Prototype ROBIAN». Dans «IEEE - (ICRA)», p. 1384–1389, 11-15 May 2002. Washington, D.C., U.S.A.

[7] G. Cheng, S-H. Hyon, J. Morimoto, A. Ude, J. G. Hale, G. Colvin, W. Scroggin, and S. Jacobsen. (2007). CB: A humanoid research platform for exploring neuroscience. Journal of Advance Robotics, 21, 10, 1097-1114.

[8] S. Alfayad, F.B. Ouezdou, F.Namoun, G. Cheng, « Lightweight High Performance Integrated Actuator for Humanoid Robotic Applications: Modeling, Design & Realization» in Proc. IEEE Int. Conf. Rob. Aut. (ICRA), Kobe, Japan, 2009.

[9] F. Gravez, O. Bruneau, F.B. Ouezdou, "Analytical and automatic modeling of digital humanoids", (IJHR), World Scientific, Vol.2, N°3, pp 337-359, september 2005.

[10] G. Cabodevila,N. Chaillet, G. Abba, Energy-Minimized Gait for a Biped Robot, pp.90-99,AMS,1995,

[11] Sanderson D.J.1; Martin P.E. "Lower extremity kinematic and kinetic adaptations in unilateral below-knee amputees during walking", Gait and Posture, Volume 6, Number 2, October 1997 , pp. 126-136(11)

[12] Rietdyk Shirley. "Lower Anticipatory locomotor adjustments of the trail limb during surface accommodation", Gait and Posture, Volume 23, Issue 3, April 2006,Pages 268-272

[13] M.Gouttefarde ,and C. M. Gosselin, " Analysis of the wrench-closure workspace of planar parallel cable-driven mechanisms", IEEE Transactions on Robotics, Vol. 22, No. 3, 2006, pp. 434-445.

[14] Duffy, J. "The Fallacy of Modern Hybrid Control Theory that is Based on Orthogonal Complements of Twist and Wrench Spaces", Journal of Robotic Systems, vol. 7(2): , 1990, pp. 139-144.