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# The Formula One Tire Changing Robot (F1-T.C.R.)

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**Abstract:**

*Formula One racing is one of the most fascinating sports ever, it is a perfect combination of high speed, technology, pressure and danger.*
*One problem associated with car racing is the time differential between teams during pits stops, which substantially affects the final results. In addition, a high percentage of the accidents in Formula One is due to pit stop problems. Changing the tires of a car while almost in motion, after reaching dangerous pressure and temperature values, is a very risky challenge, no matter how well a team is trained. Approximately 15-25 people are constantly exposed to serious dangers. The risks taken are extreme and any idea of reducing it without affecting the quality of the race should be considered.*
*Our idea is to build a fully robotized system that takes over the tire changing and refueling, process. There will practically be no need for human intervention. The system will demonstrate remarkable time accuracy, precision and low risk implications.*

## 1. GENERAL CONSIDERATIONS

In order to maintain the quality of the race, the first parameter to be optimized is the *time accuracy*. More specifically, the robot has to change the tires of any car in the same time quantum. A team can usually keep a good time while in the pits, however, this time varies too much from one team to the other. In the first version of our proposed system, a process length of 10 to 15 seconds will be achieved, and will be optimized to 6-8 seconds later. A sensor system will be implemented too. Another constraint is the *environment's limitations*. Only moderate changes in the pit stop's configuration can be allowed, due to the severe FIA (Federation Internationale De L'Automobile) regulations. Refueling is not being discussed here, however, the approach is very similar to the tire changing arms concept.

## 2. BRIEF MECHANICAL APPROACH

### 2.1. Considerations / Arms / Workspace

Our proposed robotic system consists of 5 manipulators: one for each of the tires, and a fifth one for the fuel tank. To preserve the environment of the pit stop and to assure the comfort of the team we implement suspended manipulators. The support of the 5 arms will allow a sliding motion of each arm and will not create any obstacles or driving difficulties for the pilot. The support has 2 double longitudinal branches on which the arms are to be suspended. The sliding mechanism of the arms is essential for the end effector positioning. The material used has to be resistant, of low elasticity and capable of sustaining the mass of the arms.
Each of the tires of a Formula One car is fixed to the body with a single central screw (Figure 3). This design allows a flexible end - effector with decent power and mass requirements.

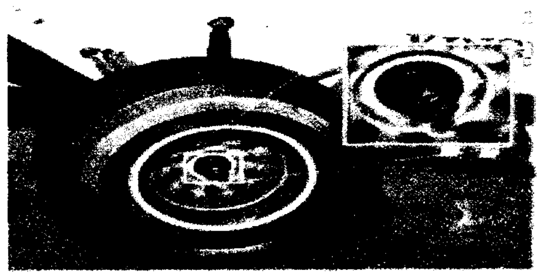

Fig. 3. Tire close-up

Each of the manipulators has a sliding range of 1 to 1.5 meters on the supports and can handle a tire in many ways. The only plane in which a good dexterity is required is the horizontal one, due to the fact that the distance from the ground and the tire's central axis is relatively constant. Based on the above-mentioned requirements, the manipulator design in Figure 4 has been derived.

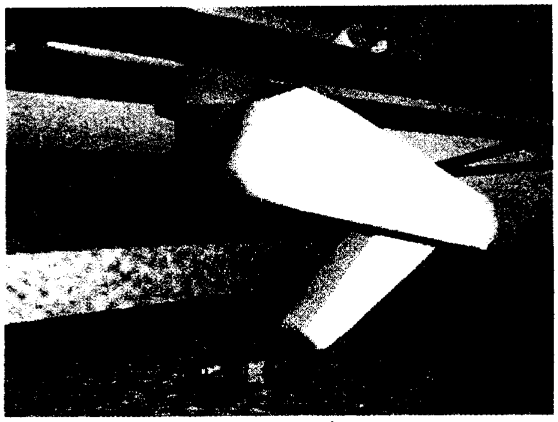

Fig. 4. Arm view

## 2.2. Tasks And Motion Related Briefings

The car arrives into the pit from a certain direction and stops in approximately the same position every time. By the time the car arrives, its exact position and direction of the tires is registered. Once it stops and is jacked up, the arms can start the *tire changing process*. For lifting the car, a simple lifting system will be positioned on the stopping platform. Each tire handling manipulator has to go through the following task sequence:

- Position the end effector as a function of the tire parameters received from the sensor system
- Rotate the end effector so that it can catch the tire
- Grab the tire
- Remove the screw
- Remove the tire from its axis and put it on the ground near the car in a convenient spot
- Change the position and grab a new tire, located in the proximity, with a new screw on it
- Reposition the end effector and mount the new tire
- Tighten the screw
- Move back in the *stand-by* position to enable the car's departure.

There are about 15 different moves to be done, each one in approximately 1 second, which would allow a process length of approximately 10-15 seconds per manipulator. All the arms work in parallel and independently. The positioning of the end effector and actually the entire set of movements required are of short distance and mainly consist of revolute steps: arm expansion/contraction, arm/end effector rotation and end effector positioning. There is a good chance that the specified time of around 1 second per move can be reduced. Four sensors are to be mounted on each tire, responsible for specifying the tire's angle and position relative to the arm. According to the information from these sensors, the end effector can position itself perpendicularly on the tire and grab it correctly. We did not have yet the chance to work on a real car, but the system can be easily adjusted to handle similar tires based on one screw. The rotation of the screw is a simple task, implying the activation of one compressed air tool with good dynamics control.

The most time consuming event is handling of the tire itself. This task requires good torque and acceleration control on the entire arm, implying the activation of all the engines, including precision sliding. Moving back in the *stand-by* position is again a simple task, completed partially when the car leaves (as long as the arms are at a safe distance from the tires, the car can go). Because of the sliding mechanism, the pilot can allow errors of up to half a meter while parking. However, the car has to be parked in relatively the same spot and direction.

## 2.3. Joint / Link Requirements And Construction

One arm is composed of 4 joints and the end effector. The first joint is prismatic and constitutes the sliding part of the system (Figure 5).

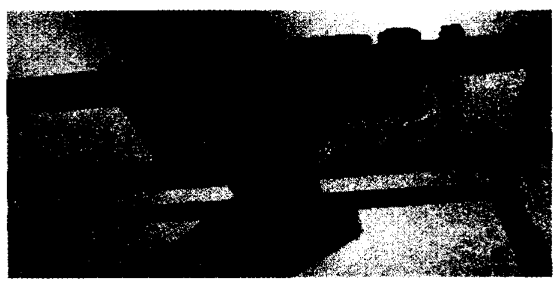

Fig. 5. The slider

Typically, the slider is activated just in the beginning of the full process, to fix the arm in an appropriate position. The friction coefficient of sliding between the support and the 4 wheels has be large enough to allow a stable braking with a precision of $1m/s^2$ and the friction coefficient of revolution has be small enough for low acceleration control.

All the engines work at high speeds and have significant mass, and so the inertia problem has to be considered thoroughly ([4, 6, 10]). To optimize the time, the arm moves from / to the stand-by position to / from the ready position in the same time with the sliding action (more details in the *Controlling* related section).

The second joint is revolute, as are all of the following ones. Figure 6 shows the joint and indicates the rotation direction.

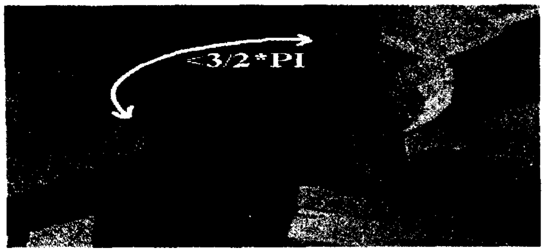


Fig. 6. Second joint (bottom left view - car side)

A revolution limitation of 3/2*PI is subjective, but it avoids kinetic or dynamic problems (e.g. singularities). The engine is fixed in the sliding part , thus concentrating the mass pressure on the support.
The third joint is closely mounted near the previous one, and together with it and the sliding joint forms the *rigid* concentration of mass and torque of the arm (Figure 7).

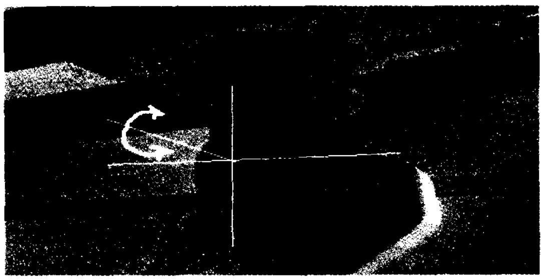

Fig. 7. Third joint (view from car side.)

In order to keep the torque high in this part of the arm and a low torque in the next joints, the engine has been attached to the axis of the previous joint. The rest of the arm has to be as light as possible as it forms the *transportable* part, which needs to be fast. The angle of rotation has been limited to less than PI/2 degrees.

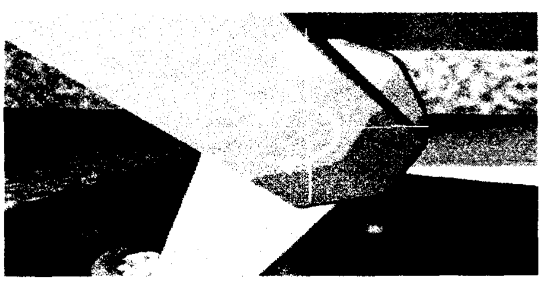

Fig. 8. Elbow joint

The last revolute joint from the arm segment is the elbow joint (Figure 8). This joint's engine has a moderate torque and is light. It is installed in the upper part of the arm, thus keeping a safe distribution of mass. The angle of revolution has been limited to PI/2 degrees. The pressure between the support and the arms has to be as small as possible, mostly because while the arms work together the support vibrations can force dislocations.
The fully extended position (at about PI for the third joint and PI/2 for the fourth joint) requires a special orientation of the end effector, for not touching the ground. The stand-by position is safe enough to offer the pilot good visibility while entering the pits.

## 2.4. The end effector (design / power / accuracy)

The end effector has to be small and light, but powerful, dexterous and quick. After going through various models, we derived the design in Figure 11.

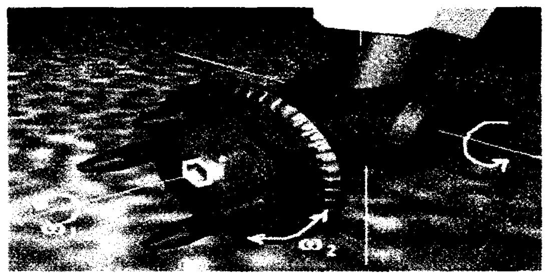


Fig. 11. End effector

This model solves all of the problems so far. First, there are no position/orientation problems. The disk type effector can rotate at a speed $\omega_2$, and reach any orientation requested by the sensor system. Having 4 identical segments, there will be no equilibrium problems during transportation. The electromagnetic forces are well distributed and allow movements within a wide acceleration range.
The revolute joint between the arm and the effector allows a rotation in the vertical plane of PI/2 degrees. The engine is light with moderate torque requirement. The engine that spins the disk with the 4 segments is installed in the pyramidal body following the cylinder, in the same spot with the compressed-air screw removal system
The only rotation that cannot be performed by this end effector is on the vertical axis, however, this is compensated by the first revolute joint, which supports most of the torque requirements and allows for good acceleration control. In this setup, the end effector can operate for almost any reachable position of the tire. Another advantage of this effector model is that the tire does not have to be perpendicular to the ground (supposing an accident has happened). The end effector would still be able to accommodate the correct orientation. However, once the tire is not perpendicular to the ground this would mean that the car has been damaged

seriously and most probably needs intervention of the team (the tire sensors prove very important here).
A small issue to be clarified is how the compressed air screwdriver finds the position of the screws: the screw driver starts a revolute task and at the same time tries to advance slowly until it "fits" the faces of the screw and fixes onto the screw.

## 3. DIRECT AND INVERSE KINEMATICS

One of the next steps is solving the direct and inverse kinematics for this specific manipulator (Figure 12).

Fig. 12. Manipulator scheme

Here, 6 joints of the arm can be seen. Using the Denavit-Hartemberg table [2], the equations for the direct kinematics can be written (the dimensions of the links are known):

$X = L + \cos(\theta_1) * (S2 * \sin(\theta_2) - S3 * \sin(\theta_2 + \theta_3) - S4 * \sin(\theta_2 + \theta_3 + \theta_4 - PI)$
$Y = -\sin(\theta_1) * (S2 * \sin(\theta_2) - S3 * \sin(\theta_2 + \theta_3) - S4 * \sin(\theta_2 + \theta_3 + \theta_4 - PI)$
$Z = S1 + S2 * \cos(\theta_2) - S3 * \cos(\theta_2 + \theta_3) - S4 * \mathrm{Cos}(\theta_2 + \theta_3 + \theta_4 - PI)$
$\theta_x = 0$
$\theta_y = 3 * PI/2 - (\theta_2 + \theta_3 + \theta_4)$
$\theta_z = \theta_1$

Where X, Y, Z, are the coordinates and $\theta_x$, $\theta_y$, $\theta_z$ the orientations of the end effector.
Solving for the inverse kinematics using direct algebraic methods [14], we obtain the following model:

$L = (Y / \tan(\theta_z))$
$\theta_1 = \theta_z$
$\theta_3 = \arccos((S2 * S2 + S3 * S3 - (X + S4 * \sin(PI/2 - \theta_y) * \cos(\theta_z) - (Y / \tan(\theta_z))) * (X + S4 * \sin(PI/2 - \theta_y) * \cos(\theta_z) - (Y / \tan(\theta_z))) - (Z + S4 * \cos(PI/2 - \theta_y) - S1) * (Z + S4 * \cos(PI/2 - \theta_y) - S1)) / (2 * S2 * S3))$
$\theta_2 = \arccos((-(S3 * \sin(\theta_3)) * ((X - (Y / \tan(\theta_z))) / \cos(\theta_1) + S4 * \sin(PI/2 - \theta_y)) + (S2 - S3 * \cos(\theta_3)) * \mathrm{sqr}((S2 - S3 * \cos(\theta_3)) * (S2 - S3 * \cos(\theta_3)) + (S3 * \sin(\theta_3)) * (S3 * \sin(\theta_3)) - ((X - (Y / \tan(\theta_z))) / \cos(\theta_1) + S4 * \sin(PI/2 - \theta_y)) * ((X - (Y / \tan(\theta_z))) / \cos(\theta_1) + S4 * \sin(PI/2 - \theta_y)))) / ((S2 - S3 * \cos(\theta_3)) * (S2 - S3 * \cos(\theta_3)) + (S3 * \sin(\theta_3)) * (S3 * \sin(\theta_3))))$
$\theta_4 = 3 * PI/2 - \theta_y - \theta_2 - \theta_3$

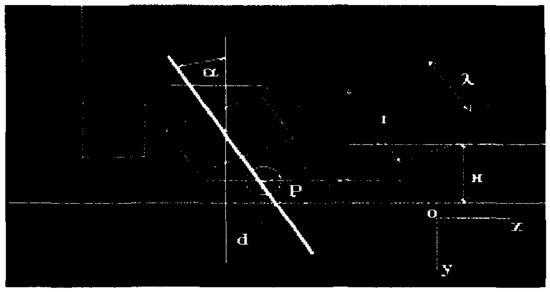


Fig. 13. Front left tire scheme (top).

The metrics referred are shown in Figure 13. For the first joint, the angle does not have to exceed PI degrees. In the initial position (stand-by), the angle will be always be positioned at 0 degrees. The following 3 joints have been referred in terms of the previous link direction. For joint 2, the angle doesn't have to exceed PI/2. The angle will reach a value close to 0 degree very rarely (when the car is situated far from the arm, 80cm or more). The initial position of this angle will be set close to PI/2, so the link will go up.
For joint 3, the reference to the previous link proves a superfluous allowance for the angle. So we use values between PI/12 and up to PI. For the stand-by position the angle will be set close to PI/12.
Joint 4 has lower limits than physically possible. The angle value will not be smaller than PI/4 and no bigger than 5*PI/4. Slightly larger angles (close to PI/4 or 5*PI/4) would cause problems holding the tire. A value of PI/2 is used for the stand-by position.
The last joint is adjusted independently from the others. The value can run from 0 up to 2*PI. A software tracking system is being built, allowing rotation of the 4 segments synchronously from the moment the sensor system gives information about the tire's position. Thus, the angle can go up to n*PI. This might also allow positioning of the segments in advance.
Decoupling of singularities is not necessary as long as the design allows their avoidance. The inverse velocity and acceleration result from the following derivations:

$$dq = J(q)^{-1} * dX$$
$$d^2q = J(q)^{-1} * b$$

Where

$$B = d^2X - d/dt * J(q) * dq$$
$$d^2X = J(q) * d^2q + d/dt * J(q) * dq$$

Where:
$q$ = the vector of joint coordinates;
$J(q), J(q)^{-1}$ = the Jacobean and inverse Jacobean of $q$
$X$ = the vector of end effector coordinates

## 4. DIRECT AND INVERSE DYNAMICS

For this type of arm the following dynamics model ([1, 3, 4, 5]) is used:

$$\tau = M(q) * d^2q + V(q,dq) + G(q) + F(q,dq)$$
$$d^2q = M^{-1}(q) * [\tau - V(q,dq) - G(q) - F(q,dq)$$

Where:
$\tau$ = the end effector torque,
**M** = the symmetric joint-space inertia matrix,
**V** = describes *Coriolis* and *centripetal* effects [5, 6],
**G** = the gravity loading,
**F** = the end effector force.

## 5. THE SENSOR SYSTEM

The variable elements derived from the sensor system that affect the inverse kinematics equations were Cx, Cy (tire center) and the angle $\alpha$ made by the tire's axis with the slider (Figure 15). These parameters are required for each tire. By receiving the XYZ coordinates of each of the 4 tire holes, (Cx, Cy) can be easily deducted.

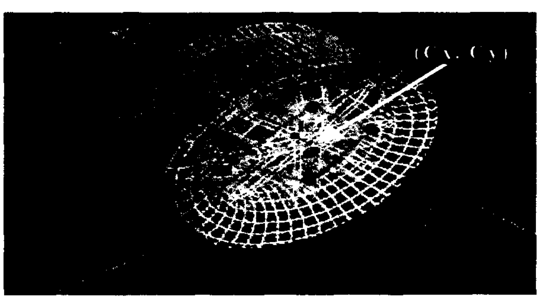

Fig. 15. Front left tire (wire-frame close-up)

There is also a need to control the number of times per second the sensor system provides data [14]. This is important to determine the car's motion. Motion recovery would allow one arm to track the tire and to have the end - effector positioned even before the car would stop, thus gaining some time.

### 5.1 Technological Orientation

According to the required sensor system tasks, one of possible implementations for this sensory system can be through a radio radar detector ([10, 12, 14]).
The receiving part of the system situated close to the scene will stay in stand-by mode and scan for signals from the tires. Once the receiver detects the sensors, this implies that the car is around, and according to the distance and the speed of the car the software will process and send the necessary information to the arm controller.
The vertical distance $\Delta y$ can be calculated from two frames having holes at about the same orientation $\omega$ (refer to the *Direct and Inverse Kinematics* section). Other tasks can be assigned to this system (i. e. analyzing the information from all the 4 tires, scanning the planarity of the car, vibrations, installation of new sensors providing different types of information, etc).

## 6. CONTROLING AND SUPERVISING

The following parameters will require continuous surveillance:
- Engine activation requests / request-reply discrepancy, internal functionality status
- Link position / orientation, requested/resulted revolution angle difference, smoothness of revolution
- Mass distribution in each arm, vibration factor evolution
- Evolution of the delay in answering
- Coordinate discrepancy between the sensor data and the actual position detected by the final effector
- Sensor's displacement in time, sensor functionality
- Support displacement, internal tension during arms motions, vibration and material response
- Temperature and pressure of the environment and of the engines, wind velocity and direction

Parameter analysis evolution and general system status

The required joints positions and orientations are always pre-simulated and compared with the ones obtained from the direct sensor output. The parameter difference is corrected using mostly PID control. We will consider for the digital feedback controllers a proportional plus derivative (PD) system ([7, 8,13]), hoping to simplify considerably the nonlinear dynamic equations, but also achieving a high update rate.

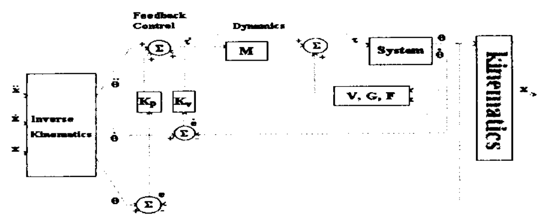


Fig. 18

### 6.1. Current Development Stage & Results

Currently the CAD/simulation module is connected with the kinematics and dynamics modules. Animation and simulations showing the entire tire changing process have been done too [11]. The next example (Figure 19) shows the torque applied on a joint for a *stand-by/full-extend* sequence, 1 second:

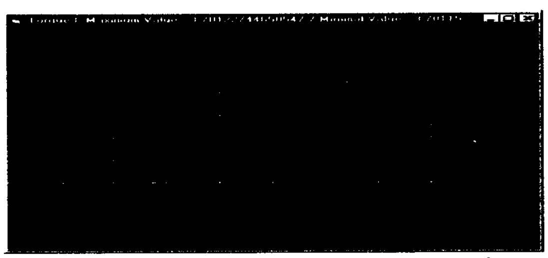

Fig. 20. Torque 3 distribution in one second.

## 7. CONCLUSIONS AND FUTURE WORK

The main advantage introduced by the system proposed here is the low-variance pit-stop time difference. Once a prototype is ready, further work will allow minimization of this time (currently estimated at 10 seconds). A second advantage is the elimination of human risks. The 5 manipulators are able not only to change the tires of a car and refuel without assistance, but also to obtain critical parameters of the car and interpret them in real-time. Future work will address the refueling manipulator and complete the integration of the entire system within the FIA restrictions.

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