Modeling and development of a quadrotor UAV

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This paper presents the conception and construction of a mini quadrotor helicopter for indoor and outdoor applications. This Unmanned Aerial Vehicle (UAV), named XSF, has a very manoeuvrable platform and is indicated to work in inaccessible spaces. Its main advantage with respect to classical 4-rotors helicopters is the ability of flipping two motors in order to obtain two more control inputs. We present its hardware architectures as well as the dynamical model used to control the UAV stabilization. The tasks scheduled by the on-board real time operating system are also introduced as well as the navigator scheme current under development.

I.Introduction

THIS paper presents the conception and construction of a mini quadrotor helicopter for indoor and outdoor applications. This Unmanned Aerial Vehicle (UAV), named XSF, has a very manoeuvrable platform and is indicated to work in inaccessible spaces such as performing inspection tasks under bridges as well as inside pipes or tanks. Its main advantage with respect to classical 4-rotors helicopters[4,5] is the ability of flipping two motors in order to obtain two more control inputs. This feature allows the XSF to have a better horizontal displacement or to create a yaw movement without translation. In this work we present the XSF's conception and implementation as well as its dynamic model, including the aerodynamic and gyroscopic effects. The swivelling of motor's support is obtained by two independent servo-motors controlled by the stabilisation scheme which provides desired angles for both motors. These angles are limited to avoid unstable situations, and the limit value is being experimentally determined.

II.XSF description

The XSF drone is a quadrotor with a 0.68m x 0.68m span (Fig. 1). It is designed in the shape of a cross and was built in carbon fibre. Each end of the cross holds a rotor including an electric brushless motor Flyware LRK-350/10, a motor speed controller Flyware rated 60A and a two-blade Graupner ducted propeller. Two side-by-side rotors turn clockwise while the two others rotors turn counter-clockwise in order to maintain equilibrium and allow the yaw motion. Compared to existing quadrotors, the XSF allows the swivelling of the supports of two motors turning in opposite senses around their pitching axis in a close manner of Vertical Take-Off and Landing planes. This allows an adequate horizontal flight and a supplementary control input for yaw motion.

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The embedded sensors and microcontroller, namely an Inertial Measurement Unit, a GPS, ultrasonic sensors and the 12V LI-POLY battery cells are located in a cylindrical box in the centre of the XSF. The embedded electronics is built around an ARM family processor running the eCos real-time operating system. In addition, a camera is used to provide images to a possible human pilot at a remote ground base. This pilot may give higher order tasks to the UAV, like waypoints, or completely take its control to better positioning of its camera. The radio link connecting the embedded system to the remote base is made by a 2.4 GHz RF transmitter.

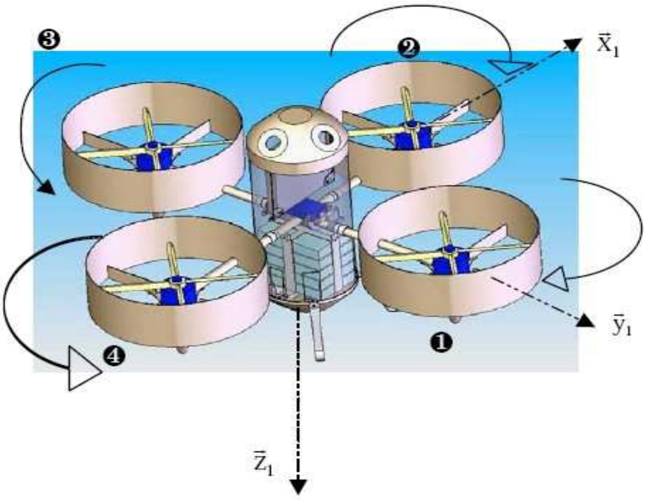

Figure 1. Representation of the UAV.

The foreseen applications for the XSF are based on pilot assistance to the human operator thanks to a wireless link between a base-station and the UAV. Nevertheless, some autonomy has to be given to the XSF. This autonomy takes place in the execution of elementary trajectories according to the current flight variables (angles, Instantaneous acceleration, and angular velocities) given by the triaxial accelerometers, magnetometers and angular rate sensors measuring both static and dynamic orientations. It is considered to estimate linear velocity using a nonlinear adaptive observer[6] that is under development[2]. Observers design for inertial navigation is indeed an open field that recently produced interesting results[3,7,8]. Finally, the surrounding obstacles are only seen thanks to 4 raw ultrasonic sensors (US sensors) (distance to ground, distances to front, left and right obstacles). Of course, intrinsic limitations of these sensors do not allow a good representation of the environment.

III.XSF dynamical model

The motion of the XSF drone can be described by the following equations[1] where $\eta_1 = [\ x\ \ y\ \ z\ ]^T$ is the position vector represented in the global reference frame, $\eta_2 = [\ \phi\ \ \theta\ \ \psi\ ]^T$ is the Euler angles vector represented in the global reference frame (roll pitch and yaw respectively), $\upsilon_1 = [\ u\ \ v\ \ w\ ]^T$ is the speed vector represented in the local reference frame (surge, sway and heave respectively) and $\upsilon_2 = [\ p\ \ q\ \ r\ ]^T$ is the angular speed vector represented in the local reference frame. In this model, the control input vector is $U = [\ \omega_1\ \ \omega_2\ \ \omega_3\ \ \omega_4\ \ \beta_1\ \ \beta_3\ ]^T$ where ω_i (i = 1 ... 4) are the angular speed of the 4 rotors, and β_1 , β_3 represent the orientation of the rotors 1 and 3. The constants k_T and k_M respectively relate rotor speeds and resulting thrust and torque, l_b is the length of each drone arm, and I_R is the rotor inertia moment constant.

$$\begin{aligned}
\dot{x} &= \cos\theta\cos\psi\, u + (\sin\phi\sin\theta\cos\psi - \cos\phi\sin\psi)v \\
&\quad + (\cos\phi\sin\theta\cos\psi + \sin\phi\sin\psi)w \\
\dot{y} &= \cos\theta\sin\psi\, u + (\sin\phi\sin\theta\sin\psi + \cos\phi\cos\psi)v \\
&\quad + (\cos\phi\sin\theta\sin\psi - \sin\phi\cos\psi)w \\
\dot{z} &= -\sin\theta\, u + \sin\phi\cos\theta\, v + \cos\phi\cos\theta\, w
\end{aligned}$$

$$\begin{aligned}
\dot{\phi} &= p + (\sin(\phi)q + \cos(\phi)r)\tan(\theta) \\
\dot{\theta} &= \cos(\phi)q - \sin(\phi)r \\
\dot{\psi} &= (\sin(\phi)q + \cos(\phi)r)\cos(\theta)^{-1}
\end{aligned}$$

$$\begin{aligned}
\dot{u} &= (-qw + rv - g\sin\theta) - \frac{k_T}{m}(\omega_1^2\sin\beta_1 + \omega_3^2\sin\beta_3) \\
\dot{v} &= (-ru + pw + g\sin\phi\cos\theta) \\
\dot{w} &= (-pv + qu + g\cos\phi\cos\theta) - \frac{k_T}{m}(\omega_1^2\cos\beta_1 + \omega_2^2 + \omega_3^2\cos\beta_3 + \omega_4^2)
\end{aligned}$$

$$\begin{aligned}
I_{xx}\dot{p} &= -l_b k_T(\omega_1^2\cos\beta_1 - \omega_3^2\cos\beta_3) - (I_{zz} - I_{yy})rq \\
&\quad - qI_r(\omega_1\cos\beta_1 + \omega_2 + \omega_3\cos\beta_3 + \omega_4) \\
I_{yy}\dot{q} &= l_b k_T(\omega_2^2 - \omega_4^2) - (I_{xx} - I_{zz})rp - rI_r(\omega_1\sin\beta_1 + \omega_3\sin\beta_3) \\
&\quad + pI_r(\omega_1\cos\beta_1 + \omega_2 + \omega_3\cos\beta_3 + \omega_4) + k_M(\omega_3^2\sin\beta_3 - \omega_1^2\sin\beta_1) \\
I_{zz}\dot{r} &= -l_b k_T(\omega_1^2\sin\beta_1 - \omega_3^2\sin\beta_3) - (I_{yy} - I_{xx})pq \\
&\quad + qI_r(\omega_1\sin\beta_1 + \omega_3\sin\beta_3) + k_M(\omega_3^2\sin\beta_3 + \omega_4^2 - \omega_1^2\sin\beta_1 - \omega_2^2)
\end{aligned}$$

The link to the ground base can be cut if the UAV goes behind an obstacle and is hidden from the base. For this reason, the stabilizing controller must be on-board and not in the base-station. This stabilizing controller is based on classical robust control techniques. In the future, these controllers will be improved in order to obtain a larger stability region allowing the drone to accept larger inclinations and speed of displacement. In the same way, we intend to include pre-defined trajectories such that the drone may choose its behaviour (fly higher, fly lower).

IV. XSF Hardware Architecture

The XSF hardware architecture is given in fig. 2. The 32 bits RISC processor is a low cost, low consumption, industry standard, ARM7TDMI[9]. Three ultra sonic range finders are used to get the front, left and right distances to obstacles. They are connected to the processor by a 100kbits/s I2C serial bus. They provide the distance measurements (D_{front}, D_{left}, D_{right}) every 66ms. A fourth US range finder situated underneath the XSF gives the distance to the ground D_{ground}. These sensors are able to measure the distances between 3cm and 6m. But the practical range is 60cm-4m. The use of this type of sensor must take into account the limitations of the US, among them: wide emission angle and variable obstacle reflection. These sensors have nevertheless been chosen because of their low power needs and weight. To compensate such limitations, a CCD camera is used to provide images to a human pilot at a remote ground base. No image treatment will be executed on-board.

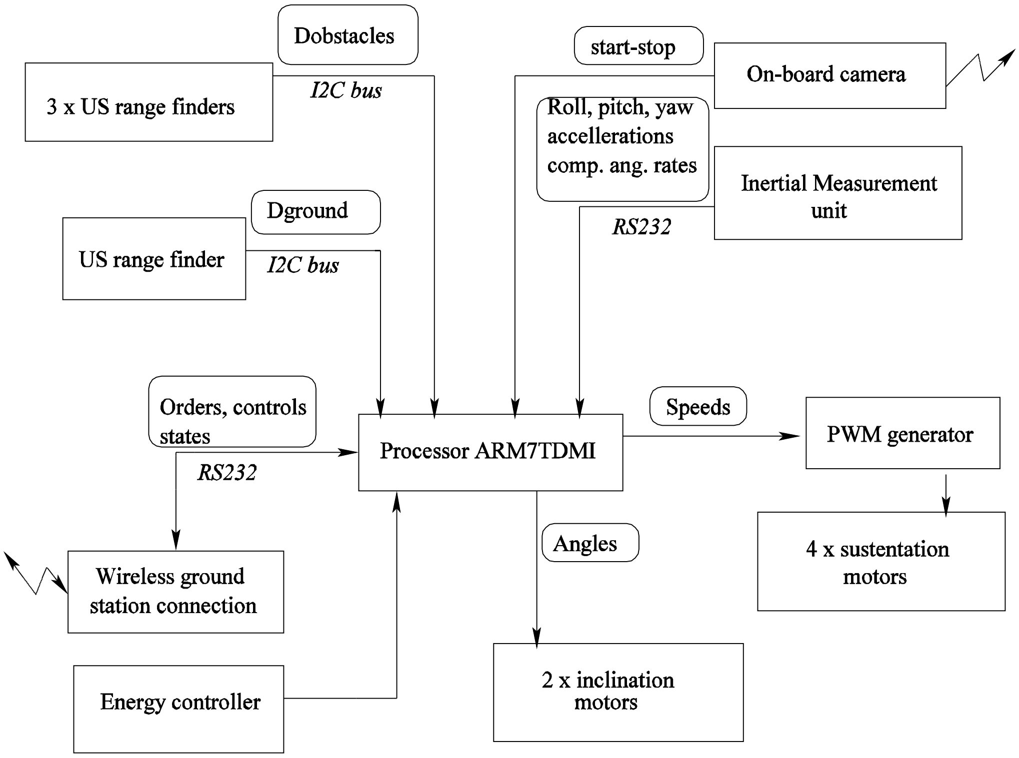

Figure 2. Hardware architecture

An Inertial Measurement Unit provides the flight variables thanks to the triaxial accelerometers, magnetometers and angular rate sensors measuring both static and dynamic orientations. The Inertial Measurement Unit communicates with the processor through a 38400bps serial line (RS232). It delivers the flight variables every 30ms.

It is expected to embed a GPS unit on the XSF in a near future. This GPS unit will allow locating the UAV in case of crash or emergency landing and will be used by the global navigation system. It should be remarked that one can not rely on GPS sensors for control since, in the first hand, considered applications are mostly either indoors, urban or close by large structures like bridges, buildings, monuments or industrial plants because these situations eclipse GPS measurements. In the second hand, the intrinsic error obtained by standard GPS units range from 3 to 10 meters. This error is too large for many applications, and then GPS is only considered for path planning and way points, but not for stabilisation. Finally, GPS unit increases the energy used by the UAV limiting its autonomy.

Energy is given by two sets of 12V LI-POLY battery cells, one to power the motors, one to power the processor and the sensors. The foreseen working time for the XSF is 20mn, what is still not enough indeed for most applications. To increase the number of battery cells onboard the UAV would have a cost in term of weight, and as a consequence, the size of UAV and motors. The problem of energy autonomy is still an open problem many groups are working on. In the future, fuel cells will maybe a solution. For all these reasons, the energy used all along the flight is measured by a specialised PSoC unit. If the remaining amount of energy stored in the battery cells reaches an experimental trimmed level, a signal is sent to the processor that will have to decide to land the UAV or drive it to return to the base.

Concerning the sustentation motor speeds, signals provided by the control scheme at the ARM7 micro-controller are sent to the static converters connected to the motors through a dedicated ASIC unit that supplies the PWM signals. Moreover, the inclination motors are controlled by two PWM signals directly generated by the ARM7.

The foreseen applications for the XSF are based on pilot assistance to the human operator assistance thanks to a wireless control-state link between a base-station and the UAV. This pilot may teleoperate the UAV to give higher orders, waypoints or completely control it to better positioning the XSF in, for example, inspection tasks. The radio link connecting the embedded system to the remote base is made by a 2.4 GHz RF transmitter. This links also allows the transmission of the UAV state as well as the flight variables.

Therefore two links to the remote ground station are always necessary: the image link and the wireless control-state link. However, these links can be broken by shadow areas and/or obstacles at the instant defined as date T0. In such cases, a connection recovery process has to be launched to recover the wireless connection in four steps:

- Step 1: The mission proceeds and a timer is activated.
- Step 2: if at the date T1 = T0 + 2s, the connection is restored, the mission proceeds, else a vertical ascendant flight trajectory is forced and go to step 3.
- Step 3: if at the date T2 = T1 + 5s, the connection is restored then the mission proceeds at the new ground distance under the control of the operator, else a controlled descent to landing behaviour is forced.

Another important unit is the failure detection unit. This unit must detect all incidents that can occur during the flight (for example, a branch blocking the propeller). In such cases, emergency behaviours must be launched. This unit is still under development, but it is based in the measurements of motor currents to detect motor gripped by measuring large currents, or motor, circuits and cables faults by measuring zero currents.

V.XSF software Architecture

The software uses the eCos[10] real time operating system (RTOS). eCos is a freeware embedded configurable operating unix-like system. It allows building a real-time operating system for specific hardware architecture. Multiple hardware platforms supported thanks to the Hardware Abstraction Layer (HAL). For the XSF, eCos has been configured to work with the Phytec ARM7/LPC-2294[12] card. Each task runs as a thread under the control of a scheduler.

The main tasks are:

- Acquisition of the current flight variables,
- Obstacles detection and altitude measurement,
- Stabilisation and motor control (sustentation and inclination),
- Global and elementary trajectory navigator,
- Self test and initialisation,
- Energy management and failures detection,
- timing.

- **Communications and synchronisations between the tasks**

The software architecture is given in fig. 3.

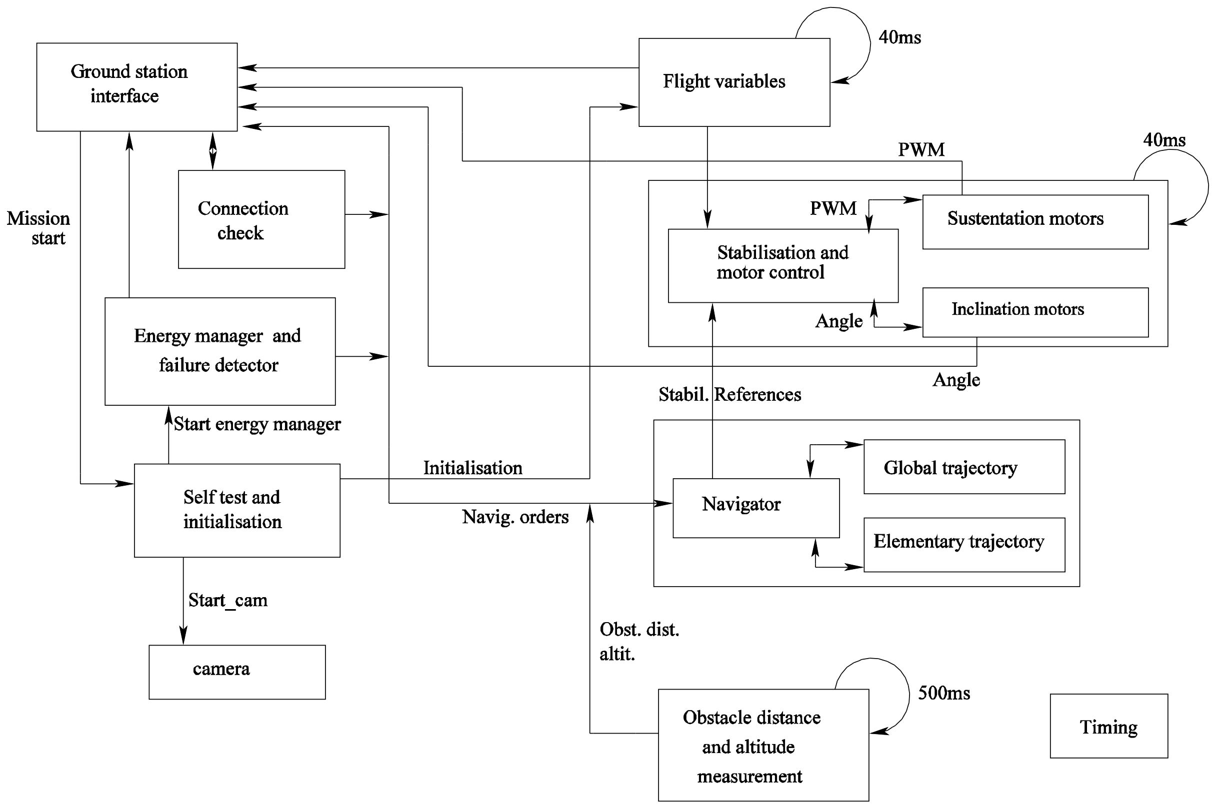

Figure 3. Software architecture

- **Timing task**

A Timing task issued from the RTC hardware system and the eCos timing manager sends synchronisation signals to the different tasks.

- **Flight variables acquisition**

This task is periodically activated. Its activation period is directly tied to the capabilities of the inertial motion unit, i.e. 40ms to get the flight variables. Flight variables are then sent to the stabilisation and motor control task and to the ground station task to be transmitted to the base station for an a posteriori analysis. These variables are also stored in on-board memory during the flight. According to the stabilisation and motor control task algorithm, a set of previous measurements are needed by the stabilisation controller. The task starts the acquisition of the first measurements before sending them to the stabilisation task. After this starting phase, this task provides to the stabilisation task the flight variables every 40 ms.

- **Stabilisation and motor control (sustentation and inclination)**

This task implements the dynamical model presented in section III. This task is executed periodically (T_Stabilisation=40ms). The task outputs are the 4 sustentation motor speeds and the two inclination angles. We chose to provide 16 discrete values for the sustentation motor speeds in a range of XXXrpm to YYYrpm. These values are written into the dedicated ASIC circuit (see section IV). It will be noted that no angular position or angular speed measurement sensors are installed on the motor axis in order to avoid overweighting the XSF.

- **Navigator, global and elementary trajectories**

The navigator takes its orders from 4 sources:

- The ground station interface: teleoperation from the human pilot,
- The energy manager: that will start a controlled soft descent firing the controlled landing elementary task,
- The obstacle detector that acts on elementary trajectories shift away or closer,
- The connection check task that runs in case of broken link with the base station. In that case, the elementary trajectories embedded on the XSF that are executed are :
  - Flying up/down vertically: Starting from a stationary flight, the XSF goes up/down according to a reference value giving the new ground distance, a climbing/descent time or a signal to be received.
  - Controlled landing: Starting from a stationary flight, the XSF lands softly.

The navigator outputs references values to the stabilisation task.

Till now, the global navigator is not implemented. Controlling the XSF is made thanks to a joystick through teleoperation.

- **Self test and failures detection**

This self test task checks the different sensors and does not allow the XSF to fly until these tests pass. The failure detection is still under development. Nevertheless, it is foreseen to detect and identify the main sources of failure, e.g. motor's current increases, and sending an emergency signal directly to the elementary trajectory task to land as soon as possible.

- **Energy management**

Energy management is perhaps the most difficult point to solve. To our knowledge, it does not exist battery cells that have both a large capacity and lightness. Fig. 4 shows the discharge function of a polymer-lithium cell.

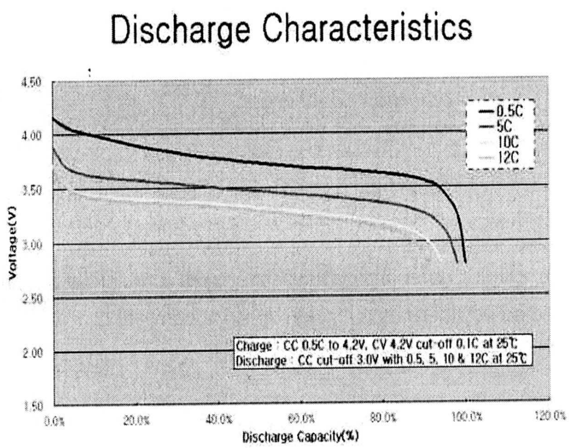

Figure 4. Screenshot of the ground station HMI.

Thanks to voltage and current sensors, the energy management unit measures the energy used by UAV during discharge. The prototype was built using a Cypress Programmable System on Chip[11] (PSoC) technology in order to reduce weight and energy needs. As shown in Fig 6, a PSoC gathers on the same chip both digital and analogical components reducing the number of additional elements needed. The energy manager also measures of the energy stored during the charging phase. It outputs 3 signals: Battery charged, Battery discharged (80%, 100%).

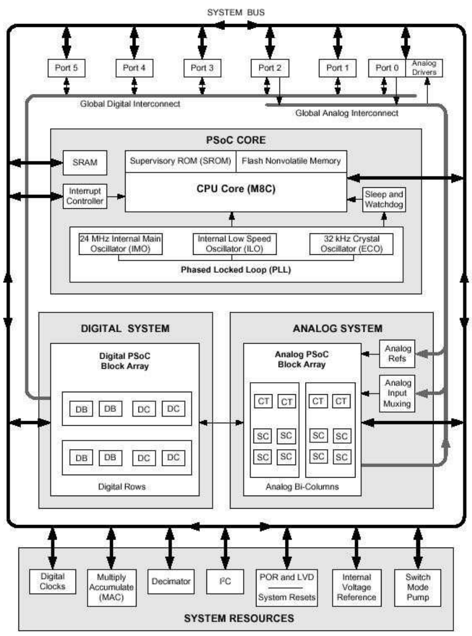

Figure 5. Example of the PSoC architecture (Cypress Microsystems document)

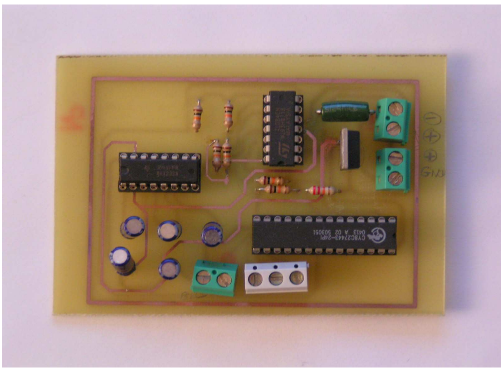

Figure 6. Prototype of the PSoC based energy manager

- **Ground station interface**

The ground station HMI situated in the ground station allows the teleoperation of the UAV thanks to a joystick meanwhile the global navigator is installed on the XSF. To date, the XSF has no autonomy but in the few elementary trajectories used mainly in emergency situations. The human operator can see all the flight variables represented in the screen and the different orders/ references transmitted by means of the wireless interface (Fig. 7.).

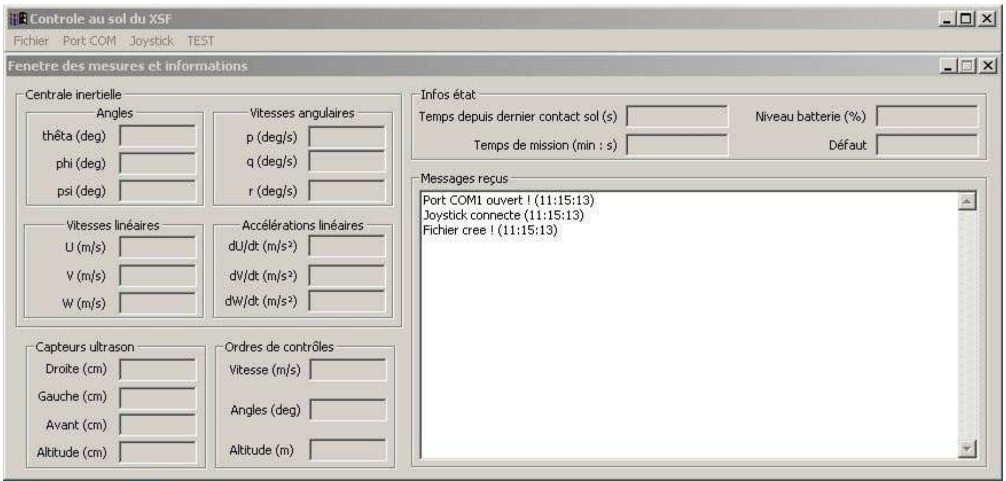

Figure 7. Screenshot of the ground station HMI

In the very simple home made protocol, the messages are composed of five bytes of controls plus the bytes of data. The message begins with a heading byte. The second byte gives the type of message. This byte allows a fast treatment of the received messages. The third byte is the message length. Data bytes and checksum follow.

Header	Type	Size	Data	Checksum	End

VI. Conclusion

This work introduced the 4-rotors helicopter named XSF. This UAV's main advantage is its ability of flipping two motors in order to obtain two more control inputs. The main structure of this vehicle is presented, its mathematical model, its embedded sensors and devices and its software structure. This drone actually flies in a test bed where is been developed future components as the decisional software, the state observer and the stabilizing controller. This configuration is very maneuverable, what will allow its use in confined environments or close structures to be inspected. As a consequence, this maneuverability has to be hard to control in real operating conditions, and the addition of the two new control inputs simplifies the task. Future steps include completing current development followed by outdoors flights. In addition, as new small sized micro-controllers are available, it will be important to include more pre-defined flight conditions like follow a ceiling or a wall until obstacles are found, or in the contrary, follow a guide as a person or another drone. Finally, the decision algorithm can be improved to take new situations into account, leaving human operator free to higher level tasks.

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