A Context-aware Communication Link for Unmanned Aerial Vehicles

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***Abstract*— The impact of contextual events for the performance of high bandwidth communication UAV link is the theme of this paper. Applications in this field have some strict quality requirements, and the communication link performance is essential for the mission success. Several events in the flight or in the surroundings can interfere with the data stream. We describe a context-controlled system which could dynamically adapt the flight in order to cope with eventualities during a mission. The main constraints of the link are discussed, and we analyze the link budget for the link considering directional receiving and transmitting antennas.**

Keywords - UAVs; Context-aware; Critical Communication System.

I. INTRODUCTION

An Unmanned Aerial Vehicle (UAV) is an autonomous flying vehicle controlled by its' embedded system. Their main uses are in the field of military applications, but other uses, such airspace surveillance and environmental monitoring operations are increasing. Figure 1 illustrates a scenario where UAVs are part of a squadron mission and work in a collaborative manner. A ***mission*** is a pre-established set of maneuvers that an UAV is due to execute in the task of pursuing a target. Usually, the mission is composed by a ***route*** (which specifies the geographical path to be flown by the UAV and its altitude), a ***timeline*** (showing possible timing requirements for the task), and a ***sensor control table*** (that stores the list of actions that the sensors must perform in order to acquire the necessary data for the task). The sensor control table is linked to the route and the timeline. Eventually the actions can be changed on-the-flight by the ***ground control station*** or in few cases autonomously. Depending on the UAV capabilities and the characteristics of the mission, a route can be ***preemptive*** (the route can be changed to meet an unexpected event during the flight) or ***non-preemptive*** (the route cannot be changed).

A ground control station is a terrestrial base instrumented in such a way that basic flight management, sensor control and monitoring are performed. The communication to the UAV can be performed in several ways. Usually, a well equipped system will have a GPS antenna, to get the proper geographical positioning and timing; an additional GPS radio link to a reference nearby point in order to calculate differential positioning; an omni-directional radio link with the ground control station for maneuvers in the vicinities of the station; a directional line-of-sight link to provide run-time communication between UAVs or with the ground when the UAV is distant from the ground control station. The more advanced UAVs [predator], [heron] also might have a satellite link which can extend the capabilities of device beyond the reach of the unidirectional link, in addition to provide backup.

The area to be covered by a mission can vary from small regions as farms and small cities to wide ones as the borders of extensive countries, like Brazil. For that reason, the communication link range has to be optimized for better results in unoccupied places or lacking in communication infrastructure.

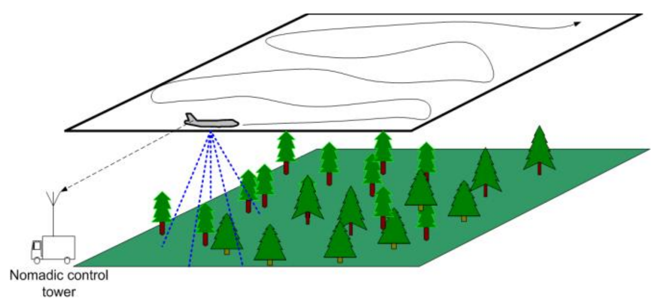

Figure 1 - An example of communication links in an UAVs mission

This paper deals with the specification and design of an adaptive context-aware directional radio link for UAVs. In special, we focus on the communication radio link composed of a ground control communication system, ground tower, ground antenna, a carrier RF signal which transport a coded data stream, UAV onboard antenna, and UAV onboard control communication system.

The communication link, once deployed in the field, can experience several interference sources (environment conditions, frequency of the carrier, gain of the antennas, geographical obstacles, etc) degrading the long distance capacity and the quality. Furthermore, the nature of the task and the mission constraints (fuel consumption, route, costs, etc.) can influence (i.e., changes in flight control) and/or be further influenced by the flight conditions and the link requirements. The contextual conditions in which the flight is subjected and the influence it has on the communication link are part of this study. In order to deal with the range of variables in a mission, it is expected that the UAV's communication link supports on-the-fly adaptation or some change based on the context alterations[10]. The awareness of the context provides the necessary knowledge to accomplish the choice of the most appropriate re-parametrization of the link communication in each situation.

The rest of the paper is organized as follows: in Section II, we survey and classify the several context-type information that can lead to an improvement of the link quality, in Section III, we discuss how the UAV system interfaces with the communication link sub-system and how this data flow can change link configuration in order to cope with unexpected signal conditions. In Section IV, we deal with some design issues when considering mission restrictions of fair connectivity while maintaining high image capturing quality and we describe in more detailed terms (i.e., FPGA sub-systems, attenuation vs modulation) and conclude the positional paper in Section V.

II. Context-Awareness to Improve Communication Link Quality

Contextual parameters are crucial in our design and they are specified in Table I. These contextual parameters can be easily gathered from a number of sources, including internal and remote sensors (eventually in the ground). Other implicit measurements can be carried out directly from the communication link in use (bandwidth, signal-to-noise ratio, packet delay, BER, etc). Finally the mission context (geography, duration, fuel consumption, etc) will impose a number of restrictions. In this way contextual parameters can create the ground bases for the adaptation of the UAV communication link.

Table I shows a thorough list of contexts that could trigger adaptation of the communication link. In the table, our goal is to classify the type of contexts based on signal quality, security, resourcefulness, environmental conditions, geography, navigational and critical restrictions. For every type of context, we illustrate the representative contextual parameters gathered by the sensors, or the like, in the UAV, and we describe in detail everyone of these parameters.

TABLE I. Contextual Parameters

Contextual Parameters		
Type of Context	***Contextual parameter***	***Contextual parameter Description***
Signal/link quality (the quality of the electromagnetic wave transporting data)	Signal to noise ratio (S/N)	The ratio of a signal power to the noise power corrupting the signal. A ratio higher than 1:1 indicates more signal than noise.
	Bit error ratio (BER)	The number of erroneous bits received divided by the total number of bits transmitted during a specified time interval.
	Bandwidth	The available data communication resources expressed in bit/s
	Delay (latency)	The time required for a data packet to travel from a specific source to a specific destination and back again.
	Jitter	The measure of the variability over time of the data packet latency across the link. A link communication with constant latency has no variation (no jitter).
	Link Availability	The ratio of the expected value of the uptime of the communication link divided by the sum of the expected values of up and expected values of down time. A=E(uptime)/(E(uptime)+E(downtime))
Security (Security is the means of ensuring that data is kept safe from corruption and that access to it is suitably controlled)	Integrity	Data that has integrity is identically maintained during the transfer operation by the link.
	Confidentiality	The guarantee that the data transfer into the link will not be disclosed.
	Authenticity	The use of some technology to prove the data is authentic, i.e. generated by an authorized source.
Resource (the amount of available resources to the UAV mission)	Energy consumption	The energy consumption in terms of battery power for data transmission and data reception.
	Fuel	The amount of gas in the aircraft, specifies the range of coverage
	Mission budget	The total sum of money set aside for a mission. This information is necessary when the link utilization is charged.
Environment	Temperature Rain Cloudiness Moisture Pressure	The state of the atmosphere with respect to elements that can interferer with the data transmission, as wind, temperature, cloudiness, moisture and pressure. Related to weather, but the amount of water determines signal degradation by absorption of electromagnetic radiation.
	Flying animals	The presence of this sort of animals should damage the UAV.
	Smoke	Smoke can cause image definition degradation and UAV instability.
	Pollution	Pollution can cause image definition degradation and damage to the equipments.
	Wind	Related to the weather, but some aerial maneuver can deal with it.
Geography	Natural features (hill, mountain)	The presence of geographical obstacle must be detected beforehand, but the interference of them on signal quality sometimes cannot be predicted.
	Obstacles	Building, tower, etc.
	Land occupation	urban or rural area, crops, river, swamp, desert, etc...
Navegability	Plane rolling	Rotational movement of the UAV around its longitudinal axis.
	line of sight	a straight line connecting two points

Contextual Parameters		
Type of Context	***Contextual parameter***	***Contextual parameter Description***
	Route	air flight mission planning
Mission criticality	Several	Several critical aspects that could be incorporated in the mission

Whenever deployed in the field, we combine some of this contextual information we may have to deal with drastic adversities in the radio communication link. Figure 2 shows the architecture to gather this information and manage it in order to support communication link adaptation.

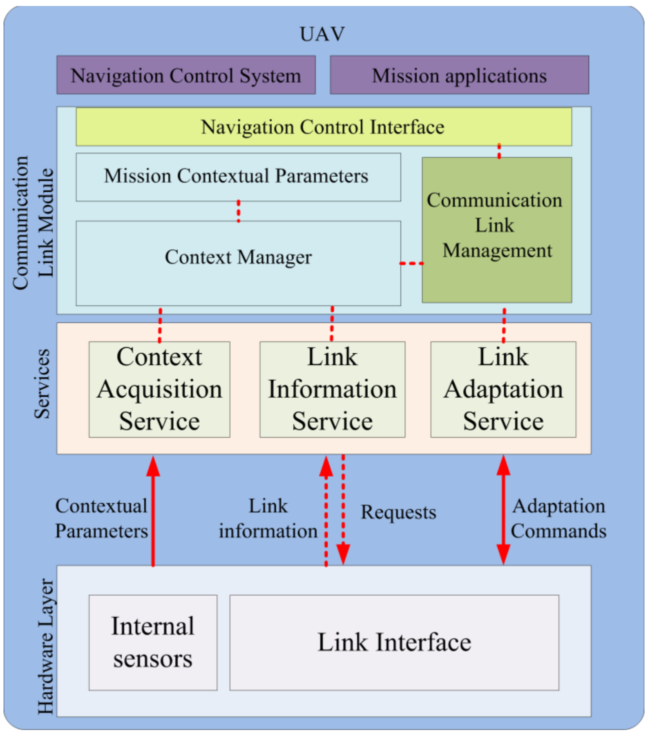

Figure 2 – Context-awareness architecture in UAV

The architecture is composed by three services (Context Acquisition Service, Link Information Service, and Link Adaptation Service) that gather information from the Hardware Layer to the Communication Link Module, and trigger commands to adapt the communication link. The set of information includes contextual parameters, link information requests and responses, and adaptation commands. The Context Manager updates the types of context using the Mission Contextual Parameters, and contextual parameters gathered from the Context Acquisition Service and from the Link Information Service. The Communication Link Management decides for a specific adaptation action based on a set of rules using the contexts provided by the Context Manager. For example, consider the link strength diminishing while the aircraft is rolling due to the mission restriction of maintaining connectivity at all costs. This may trigger many types of adaptation commands from the Communication Link Management using the Link Adaptation Service, such as change of the modulation (B-PSK instead of a 64-QAM) in order to cope with a increasingly bad link, or even in some drastic cases with changes to the frequency been used, as one would do using 802.11 and all the compatible versions (a/b/g) embedded in the single system. Finally, the Navigation Control Interface provides to the Navigation Control System and to other mission applications the critical information so to comply with the link conditions.

In this way, the contextual information will interfere with UAV overall control and with the embedded applications in order to keep the communication necessities of the mission.

III. Interfacing with the UAV

In this section, we describe one UAV architecture which presents a block diagram representing a typical UAV hardware architecture [1]. The architecture uses four processors in a unique embedded board.

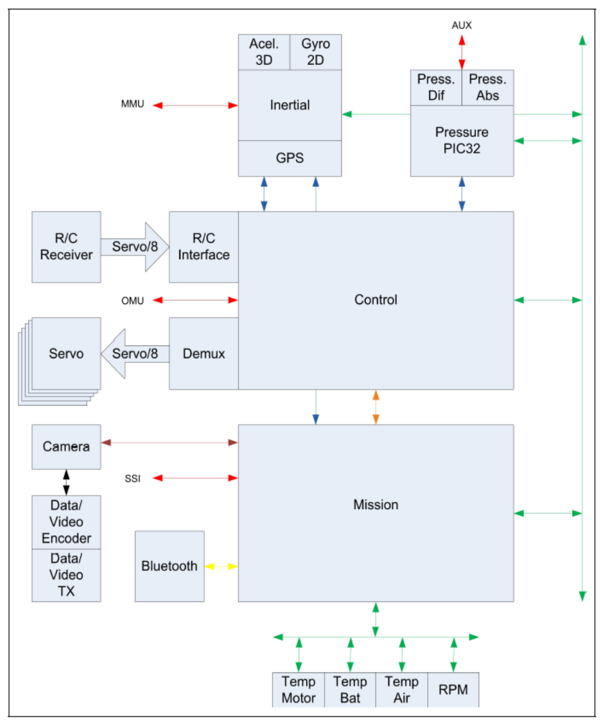

Figure 3 - UAV Overall System

The first processor (also called Mission) is responsible for the mission accomplishment, i.e., the execution of the previously planned tasks. The second processor (also called Control) is responsible for the UAV navigability. It receives basic pilot-like commands from the mission processor and from the control tower. Finally, the last two processors implement the processing stream of two main sets of flight sensors: (a) the inertial unit integrating a GPS receptor and a module for terrestrial magnetic field measurement (this one responsible to determine the UAV altitude), and (b) a barometric unit to measure the aerodynamic velocity, barometric altitude and the UAV ascension rate [1]. All these subsystem can be connected to the Navigation Control Interface (see Figure 2) in order to response to the actions suggested by the Link Communication Management Module.

IV. DESIGN ISSUES FROM THE COMMUNICATION LINK

In this session, we describe some of the design issues related to the utilization of context aware data and the tradeoffs of designing an adaptive UAV link. In particular, we describe in *A*, an equation-based scheme to recalibrate or dynamically change the gain of the antenna depending on the attenuation conditions. Afterwards, we describe technique to cope with lack of line-of-sight (LOS) in *B*, the use of adaptive modulation scheme is described in *C*. We finish the design decisions describing how to cope with multi-path fading in *D*, maximize throughput exploring spatial diversity through multiple antennas in *E* and some preliminary diagram of the implementation of the design in *F*.

A. Attenuation Design

The easiest approach in wireless communication link design is to utilize a fixed signal strength in the transmitter that guarantees the communication over the pre-determined range compensating for a certain fading margin, through calculations of the attenuation levels. The attenuation in free space, also called free-space loss, of an electromagnetic wave is a function of the propagated distance, d, and the frequency, f. The total attenuation in dB [7] can be calculated through the following equation (1). In this, the measurement units of d and f are kilometers and megahertz respectively and c=32.45dB:

$$a_0(d,f) = 20\log(d) + 20\log(f) + c \tag{1}$$

Applying the attenuation in free-space, a_0, and the attenuation inside wires and connectors called a_r, and also the threshold signal from the reception, P_r(dBm), we can easily estimate the minimum signal strength we will need in the UAV transmitter [8], P_t(dBm), according to equation (2). The parameters G_t and G_r are the respective antenna gains utilized in the transmitter and receptor, respectively.

$$P_t = P_r + a_0 + a_r - G_t - G_r \tag{2}$$

The communication equipment installed in the UAVs is likely to have restriction of size and weight, for this reason, we anticipate that UAVs may have to be build using small antennas. The most "off-the-shelf" solution in this case employs omni-directional antennas (or the monopole type), despite of that, we might want to increase the range covered using components to turn the antenna into directional ones with high gain (Parabolic-like).

B. Coping with Lack of Line of Sight (LOS)

In a recent work, Nakamura et al. have discussed a control technique that exploits the redundancy of robots arm joints in order to predict movements [2]. Gans et al. [4] then applied such concepts to solve the problem of surveillance of a large area through UAVs equipped with video cameras while at same time managing to guarantee the connectivity at all times. by making the UAVs close to each other, in a control theoretic coordinated fashion. However, their approach do not take into account the restrictions imposed by directional link that could be violated due to VANTs fast movement or by natural obstacles (such as mountains or large trees). A more realistic approach would use in addition the LOS and the distance to further maintain the connectivity, and this would need a pro-active controller of the link, that has to be able to detour smoothly the pre-established trajectory in the mission to a new route in order to guarantee connectivity.

C. Exploiting Multibit Modulation

The wireless standards 802.11 and 802.16 were designed to exploit some degree of contextual information to solve issues of weak signal, availability and packet loss. In these standards, there is a constantly monitoring daemon measuring the signal-noise ratio (SNR) in order to alternate the modulation technique to be used among several types BPSK, QPSK, 16-QAM e 64-QAM. Whenever the SNR is high (signal strong compared to noise), the system uses the modulation that generates more bits per symbol (i.e. 16-QAM and 64-QAM), and, on the other hand, whenever the SNR is low it is used a modulation that presents a low bit error probability (more robust to interference and fading) such as QPSK and BPSK). In our architecture the Communication Link Management alternate modulation scheme when SNR change.

D. Copying with Multi-Path Fading

Typically, UAVs are engaged in missions to recognize, patrol, explore, monitor large areas of land. These conditions could turn the link subject to interference by natural phenomena that can degrade the transmission performance. In particular, for long range UAV communication, we could experience multipath fading effects (the most significant) and long delays.

The multipath problem can be solved in the UAV through a transmission technique that resembles Orthogonal Frequency Division Multiplexing (OFDM). By dividing the available spectrum band, B, in N subcarriers, we reduce drastically the effect. In fact, as much more sub-carries one has, less effect it will experience, however, there is a cost in terms of complexity of the hardware and susceptibility to the Doppler Effect. 802.11 and 802.16 use OFDM to solve multipath propagation problems.

The Doppler Effect happens in UAVs that are approaching each other at high speed. In this area, Wu et al.

[3] investigated the variability of the SNR as a function of the relative velocities between VANTs, and Robertson and Kaiser [5] described a method to ameliorate this effect through the correction of the local oscillator frequency in order to minimize the ICI (Inter subcarrier interference). As an alternative, we could reduce slightly the number of sub-carries N to achieve similar objective. The Communication Link Management must be able to choose appropriate number of subcarriers because it interferes in multipath effects.

E. Coping with Throughput Difficulties

One desirable goal in any communication design is to have control of the throughput from UAV to ground and vice-versa in order to send the acquired information (such as pictures or high resolution video) with the specified quality. One approach that is interesting is to exploit spatial redundancy through more than one antenna using a technique like MIMO [6]. However, since the aircraft is constrained in terms of the payload, it is more appropriate to design the multiple antenna scenario in the ground base station. According to the equation (3), the known capacity limit, given in bits/Hertz, using SIMO at the UAV and MISO at the ground base station, is calculated. In that equation M is the number of antennas in the ground station and E_s/N_0 is the signal-to-noise ratio [6].

$$C = \log_2\left(1 + M\frac{E_s}{N_0}\right) \qquad (3)$$

In conditions where the signal-to-noise ratio is degraded, the capacity will decrease, so the bandwidth must be increased to keep constant throughput.

F. High-level Prototype Implementation

Finally, we envision that it would be appropriate to give flexibility to the communication system through a implementation that uses a mixture of a sophisticated antenna circuitry combined with low powered customized FPGA designs ready for several of the radio specifications in software modules, such as modulation, filters and others. The Figure 4 presents such a design where we show only the detail of the interface to the antenna.

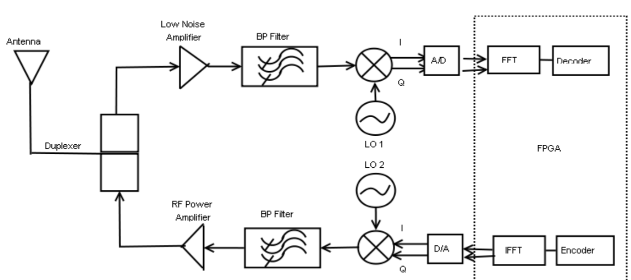

Figure 4 - FPGA to perform low-powered radio functions

G. Case Study

Let's consider a link with maximum range, R=100km, transmitter power, P_t=26dBm, receiver threshold, P_r=-80dBm, attenuation in the line and connectors, a_r=3dB. The receiver and transmitter are equipped with parabolic antennas. Figure 5 shows the attenuation for this range.

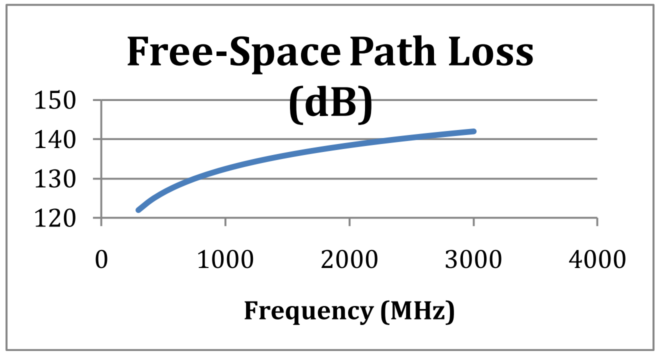

Figure 5 – Free-Space Path Loss (dB)

The gain of a parabolic antenna is

$$G = 10\log\eta\frac{\pi^2 D^2 f^2}{c^2}, \quad (4)$$

where D is the parabolic diameter, f is the operation frequency, c = 3.10^8 and η is the efficiency of antenna [9]. For simplicity we considered η =1.

We derive a closed formula for the parabolic diameter at the radio receiver and transmitter as a function of frequency:

$$D = \frac{c}{\pi f}\sqrt{10^{\frac{a_0(f)+a_l-P_t+P_r}{40}}}, \quad (5)$$

Figure 6 shows the diameter for each parabolic antenna. At the frequency of 2,4GHz we need a parabolic antenna with 33.5cm of diameter. We must choose parabolic antennas with small diameter, because UAVs don't support heavy loads. Aerodynamic constraints are other reasons to this choice.

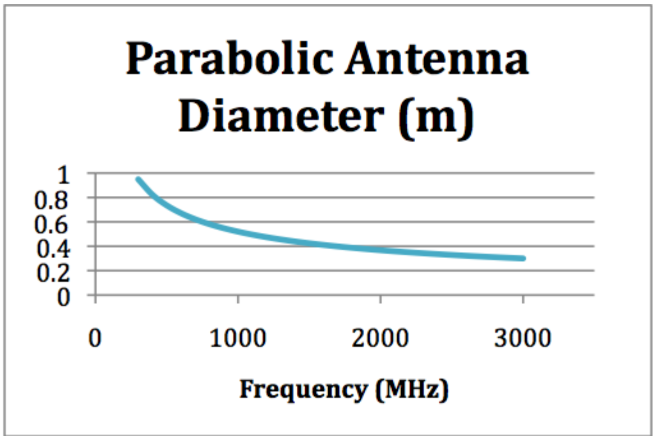

Figure 6 – Frequency (MHz) x Parabolic Antenna Diameter (m)

V. CONCLUSIONS AND FURTHER DIRECTIONS

In this work, we described some work done for the design of a communication link for UAVs. The design is heavily based on context-aware information to re-parameterize and adapt the link in order to sustain its critical goals in a mission. The idea is coupling the UAV common subsystem and sensors to the communication link and control. In harsh conditions, the link could recover in a soft mode through changes in link-level parameters such as power, adjust gain, improving FEC and change antenna directionality while a hard mode could be drastic as to change the communication used frequencies and changing the mission planner in order to cope with aerial maneuvers that are better suited to maintain the UAV-ground connectivity. UAVs must be equipped with small antennas. We conclude that it is possible to reduce the antennas dimensions without increasing the output power or receiver sensitivity (Figure 6).

In the future, we intend to prototype our design and field experiment in collaboration with a team that developed a real UAV in Brazil within the National Science Institute for Critical Embedded Systems. We also intend to incorporate multiple antenna and handover capabilities in an urban scenario.

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