

Phase 1: RFCAR

Product concept, foreseen specifications, planning, tests and initial design

Nuno Rodrigues A85207, Hugo Carvalho A85156, Hugo Ferreira A80665,
João Faria A85632, João de Carvalho A83564, José Mendes A85951,
José Miguel Alves Pires A50178*

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*a50178@alunos.uminho.pt

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1 Product concept: Radio Frequency Camera Assisted Rover (RFCAR)

The envisioned product consists of a remote controlled car used to assist exploration and maintenance domains. For this purpose, the vehicle should contain a remotely operated camera feeding back video to the user. Additionally, the vehicle must contain odometric sensors to assist in driving and prevent crashes when user is not in control, e.g., when connection is lost. The vehicle can be used for exploration of unaccessible areas to human operators like fluid pipelines and other hazardous sites.

2 Foreseen product specifications

2.1 QFD — Quality Function Deployment

The use of a QFD ‘Quality House’ was opted as it is an efficient method of defining requirements laid out for the project and convert them into somewhat detailed engineering specifications in order to fullfill those requirements, along with several tools that allow to define the relations existing between the latter and the former.

The QFD works by using a matrix where the project requirements will be laid out as rows and the engineering specifications as columns; in the intersec-

tions lie a number representing the strength of the relationship requirement-specification.

Along with the requirements, the importance given to each is also specified, ranging from 1 (lowest importance) to 5 (highest importance) these, along with the number at each intersection, will be used to calculate the Weighted Score of each requirement and the Technical Importance Score of each specification. These results will in turn be used to calculate the importance of each specification and thus assign priorities for the Design Team.

Figure 1 shows the ‘Quality House’ for the RF CAR containing:

- Customer Requirements: Safe to Operate, Obstacle Avoidant, Fast, and so on.
- Functional Requirements: Cost of Production, Maximum Velocity, Engine Power, amongst others.
- The Intersection Values (referencing the strength of the requirement-specification correlation):
 - 0: No Relation.
 - 1: Weak Relation.
 - 3: Moderate Relation.
 - 9: Strong Relation.
- The Analytical Results, depicting, quantifiably, the relevance of each entity:
 - Weighted Score, for the Requirements.
 - Technical Importance Score, for the Specifications.
 - Importance and Priority Rank, which are the main conclusion for which the QFD was used.

For instance, the ‘engine power’ specification and the ‘fast’ requirement have a very strong correlation (9) since the power of the engine is directly responsible for the velocity of the car.

With the QFD, the priorities ranks were obtained supplying the Design Team with a straightforward guideline. For instance, the cost of production should be prioritized over all other specifications, followed by the maximum velocity, Ramp-Up Speed Time and so on. On the other hand, the engine expectancy is of little to no consequence (note that the importance added up to a mere 3%), followed by most of the camera-related specifications, this

could be regarded as a point of discussion, which should be prioritized? The functionality of the car or the the feedback provided by the camera?

With the last point in mind, the QFD has the advantage of allowing further discussion, simply by changing the importance of a requirement the priority ranking will change, ergo the priorities can be altered, easily and efficiently, if deemed appropriate.

Quality Function Deployment

Project Title:	RF-CAR
Project Leader:	Nuno R
Date:	3/4/201

You need only to fill the white and blue cells.

You need only to fill the white and blue cells.																								
1: low, 5: high Customer Importance rating	Desired direction of improvement (↑, 0, ↓)										Relationships:													
	Functional Requirements (How) →																							
	Customer Requirements - (What) ↓																							
	Battery Life (Autonomy)	Battery Temperature	Max Distance to Obstacle	Maximum Velocity	Frame Rate	Camera Range	Resolution	Engine Expectancy	Comms Range	Engine Power	Cost of production	Ramp-up Speed Time	Dimensions	Comms Speed	Mass/ Weight									
1	5	0	9	9	9	0	0	0	1	9	9	3	0	3	260									
2	5	0	0	9	9	0	0	0	0	9	0	9	0	3	195									
3	4	0	0	0	0	9	9	9	0	1	0	0	9	0	184									
5	1	3	0	0	0	0	0	3	9	1	3	9	0	9	37									
6	4	0	0	3	0	0	0	9	0	9	9	0	9	0	156									
8	2	9	3	3	9	0	0	3	0	9	3	9	1	9	116									
4	4	3	3	3	3	3	9	3	9	9	3	3	3	3	252									
3	3	9	3	0	9	1	0	1	3	3	9	1	3	3	171									
3	3	0	0	3	0	0	0	0	1	0	1	9	0	0	42									
Technical importance score		60	72	129	147	51	48	75	30	93	98	182	144	113	93	78	1413							
Importance %		4%	5%	9%	10%	4%	3%	5%	2%	7%	7%	13%	10%	8%	7%	6%	100%							
Priorities rank		12	11	4	2	13	14	10	15	7	6	1	3	5	7	9								
Current performance																								
Target																								
Benchmark																								
Difficulty																								
Cost and time																								
Priority to improve																								
1: very easy, 5: very difficult																								
1: low, 5: high																								

Figure 1: Foreseen product specifications:Quality Function Deployment for the RFCAR

The foreseen product specifications are listed as topics below.

2.2 Cost

The QFD method used pointed out the cost of the product as the most relevant aspect for the design team (see Section 2.1). Obviously, without the desired functionality, the cost is irrelevant. Nonetheless, it is important to estimate the product cost to evaluate its viability and, consequently, of this project. For the product's cost estimation should be taken into account the development effort (man hours), the components' cost, manufacturing and assembling cost, and the shipment cost.

2.3 Autonomy

The vehicle is operated off-the-grid, thus, a portable power source must be included. The autonomy refers to the time interval between battery fully charged and safely discharged and should be observed for the following scenarios:

- No load and vehicle operating at maximum speed;
- No load and vehicle operating at mean speed;
- Maximum load and vehicle operating at maximum speed;
- maximum load and vehicle operating at mean speed.

2.4 Velocity

The vehicle must be operated within a safe range of velocity, while also not increasing excessively the power consumption. Thus, these velocity boundaries should be tested in the absence of an external load and in the presence of the maximum load.

2.5 Safety

Safety is paramount in product design, especially considering the vehicle is to be remotely operated. Safety can be analysed in two ways, considering the preservation of people and goods. For the former, it is important to assure safe user operation as well as safe human interaction — the vehicle may encounter several people along its path, but it must not inflict any damage. For the latter, the vehicle under operating conditions must not inflict

any damage to goods. Thus, in the presence of conflicting user commands violating the safety of people and goods, the local system should override them, taking corrective measures to prevent it. The same holds true if the communication between user and system is lost.

2.6 Image acquisition

The vehicle is equipped with a camera to assist the user in its navigation, thus, requiring it to be fed to the user's platform appropriately.

2.6.1 Frame rate

Frame rate refers to the frequency at which independent still images appear on the screen. The higher the frame rate, a better image quality is obtained but the processing overhead increases as well, so a compromise must be achieved between the quality of the image and the processing overhead required. The minimum frame rate defined must be such that allows a clear view of the video.

2.6.2 Range

How far can the camera capture images without losing resolution and record them. The range must be such that allows the user to see the obstacles when the car is heading to them and provide enough time to change the direction.

2.6.3 Resolution

The amount of detail that the camera can capture. It is measured in pixels. The quality of the acquired image is proportional to the number of pixels but a greater resolution requires a greater data transfer and processing overhead, thus, a compromise must be achieved. The minimum resolution must be such that provides the least amount of information required for the user.

2.7 Load

The remotely controlled vehicle can be used in applications involving external load carrying, e.g., packet delivery. For this purpose it is important to determine the maximum load the vehicle can carry safely at the minimum velocity defined. As the load increases, also increases the power consumption, diminishing the autonomy. Thus, a compromise between safe motor operation and power consumption must be found.

2.8 Overall System latency/responsiveness

The overall system latency is the sum of all systems' latencies, which must be under a maximum tolerated value for the user.

2.9 Communication

2.9.1 Reliability

A communication is reliable if it guarantees measures to deliver the data conveyed in the communication link. As reliability imposes these measures, it also adds overhead to the communication protocol, which must be considered depending on the case. For example, for the devised product, an user command must be acknowledged to be processed, otherwise, the user must be informed; on the other hand, losing frames from the video feed is not so critical — user can still observe conveniently the field of vision if the frame rate is within acceptable boundaries.

2.9.2 Range

The communication protocols have a limited range of operation, and, as such, regarding the environment on which the car is used the range can be changed. The range refers to the maximum distance allowed between user and system for communication purposes.

2.10 Sensibility

The movement of the car will be determined by the tilt movement of the smartphone. Sensibility refers to the responsiveness of the car on the minimum smartphone tilt movement. The sensibility must be in an range of values in which small unintentional movements will be enough to change the state of the car and it does not take big smartphone tilts for the car to move.

2.11 Closed loop error

The velocity, direction and distance to obstacles must be continuously monitored to ensure proper vehicle operation. The closed loop error must then be checked mainly in three situations as a response to an user command:

- velocity: the user issued an command with a given mean velocity, which should be compared with the steady-state mean velocity of the vehicle.

- direction: the user issued an command with a given direction, which should be compared to the vehicle direction.
- distance to obstacles: the user issued an command with a given direction and velocity which can cause it to crash. The local control must take over control, preventing this to happen, and the final distance to the obstacles must be assessed and compared to the defined one.

2.12 Summary

Table 1 lists the foreseen product specifications.

Table 1: Specifications		
	Values	Explanation
Autonomy	4 h	Time interval between battery fully charged and safely discharged
Minimum Velocity	0.1 m/s	Minimum velocity at which the car can operate safely
Maximum Velocity	1 m/s	Maximum velocity at which the car can operate safely
Maximum Load	0.5 kg	Maximum load the car can safely carry
Frame Rate	60 fps	Frequency at which independent still images appear on the screen
Camera Range	20 m	How far can the camera capture images without loosing resolution
Camera resolution	480p	Amount of detail that the camera can capture
Comunication Range	50 m	Maximum distance between the car and the smarphone without losing connection
Velocity Error	5 %	Maximum difference between desired and real velocity
Direction Error	5%	Maximum difference between desired and real direction
Distance Error	5 %	Maximum difference between desired and real distance to the obstacle
Dimensions	20x12x5 cm	Dimensions of the car
Weight	0.5 kg	Weight of the car

3 Planning

In fig. 2 is illustrated the Gantt diagram for the project and in fig. 3 the tasks' descriptions. It should be noted that the project tasks of Analysis, Design, Implementation and Tests are performed in two distinct iterations as corresponding to the Waterfall project methodology.

Due to unpredictable circumstances, limiting the mobility of team staff and goods, the implementation stage will not be done at full extent, but rather at a simulation stage. Thus, to overcome these constraints, the project focus is shifted to the simulation stage, where an extensive framework as to built to model the system operation, test it, and providing valuable feedback for the dependents modules. As an example, the modules previously connected just by an RS232 link, must now include upstream a web module (TCP/IP) — the data is now effectively sent through the internet, and must be unpacked and delivery serially as expected if only the RS232 link was used.

The tasks are described as follows:

- Project Kick-off: in the project kick-off, the group is formed and the tutor is chosen. A brainstorming about conceivable devices takes place, whose viability is then assessed, resulting in the product concept definition (Milestone 0).
- State of the Art: in this stage, the working principle of the device is studied based on similar products and the system components and its characteristics are identified.
- Analysis: In the first stage — Analysis 1 — contains the analysis results of the state of the art. It should yield the specifications document, containing the requisites and restrictions to the project/product, on a quantifiable basis as required to initiate the design; for example, the car maximum velocity must be, at maximum, 2 m/s . The second stage — Analysis 2 — contains the analysis of the first iteration of the development cycle.
- Design: it is done in two segments: modules design — where the modules are designed; integration design — where the interconnections between modules is designed. It can be subdivided into *conceptual design* and *solution design*.
 - In the conceptual design, several problem solutions are identified, quantifying its relevance for the project through a measur-

ing scale, inserted into an evaluation matrix, for example, Quality Function Deployment (QFD).

- In the solution design, the selected solution is developed. It must include the solution modelling, e.g.:
 - * Control system design: analytically and using simulation;
 - * Transducer design: circuit design and simulation;
 - * Power system design: power supply, motors actuation and respective circuitry design and simulation;
 - * Communications design: communication protocols evaluation and selection;
 - * Software design: for all required modules, and considering its interconnections, at distinct levels:
 - frontend level: user interface software, providing a easy and convenient way for the user to control and manage the system.
 - framework level: software required to emulate/simulate and test the required system behaviour, providing seamless interfaces for the dependents modules
 - backend level: software running *behind the scenes*, handling user commands received, system monitoring and control.
- Implementation: product implementation which is done by modules and integrated. Once again, it should be noted that the implementation is mostly done in simulation and coding stages, due to the aforementioned constraints. In the first stage, the implementation is done in a prototyping environment — the assisting framework developed, yielding version alpha; in the second stage it must include the coding on the final target modules, yielding prototype beta.
- Tests: unit tests — by modules — and integrated tests are performed. Tests are generally considered as those performed over any physical component or prototype. Here, it is used as a broader term, to reflect the tests conducted into the system and the several prototypes.
- Verification/Validation: in normal circumstances, after the alpha prototype is built the specifications listed in the analysis must be verified and the prototype validated by an external agent (an external user to the group). Due to abnormal circumstances, the verification must

now be performed, not on the physical prototype, but over the chain of modules developed, checking their performance against the specifications listed, i.e., subsystem verification. System verification may be performed to validate overall function, but not for quantifiable measurement, due to the latencies involved. Regarding validation, once again, there is limited access to the physical modules, specially for an external agent, thus, it should be limited to user interface validation.

- Delivery: — project closure encompassing:
 1. Final prototype
 2. Support documentation: how to replicate, instruction manual.
 3. Final report
 4. Public presentation

4 Tests

Tests are generally considered as those performed over any physical component or prototype. Here, however, it is used in a broader sense, to reflect the tests conducted into the system and the several prototypes, under the abnormal present circumstances. The tests are divided into verification and validation tests.

4.1 Verifications tests

The verifications tests are tests performed internally by the design team to check the compliance of the foreseen specifications. These tests are done after the prototype alpha is concluded.

4.1.1 Functionality

The remotely operated vehicle is composed of several modules distributed along several different platforms, some of which distanced from each other. In the present abnormal circumstances, this is even more true. Thus, the proposed sets of functionalities should be tested in the integrated system, by tracking and analysing the user commands issued along the way until it finally reaches the vehicle, assessing if it is correctly processed. For example, if the user issues the vehicle to move to a given place, the message sent to the vehicle must be signaled in each endpoint hit, and the vehicle should move to that place.

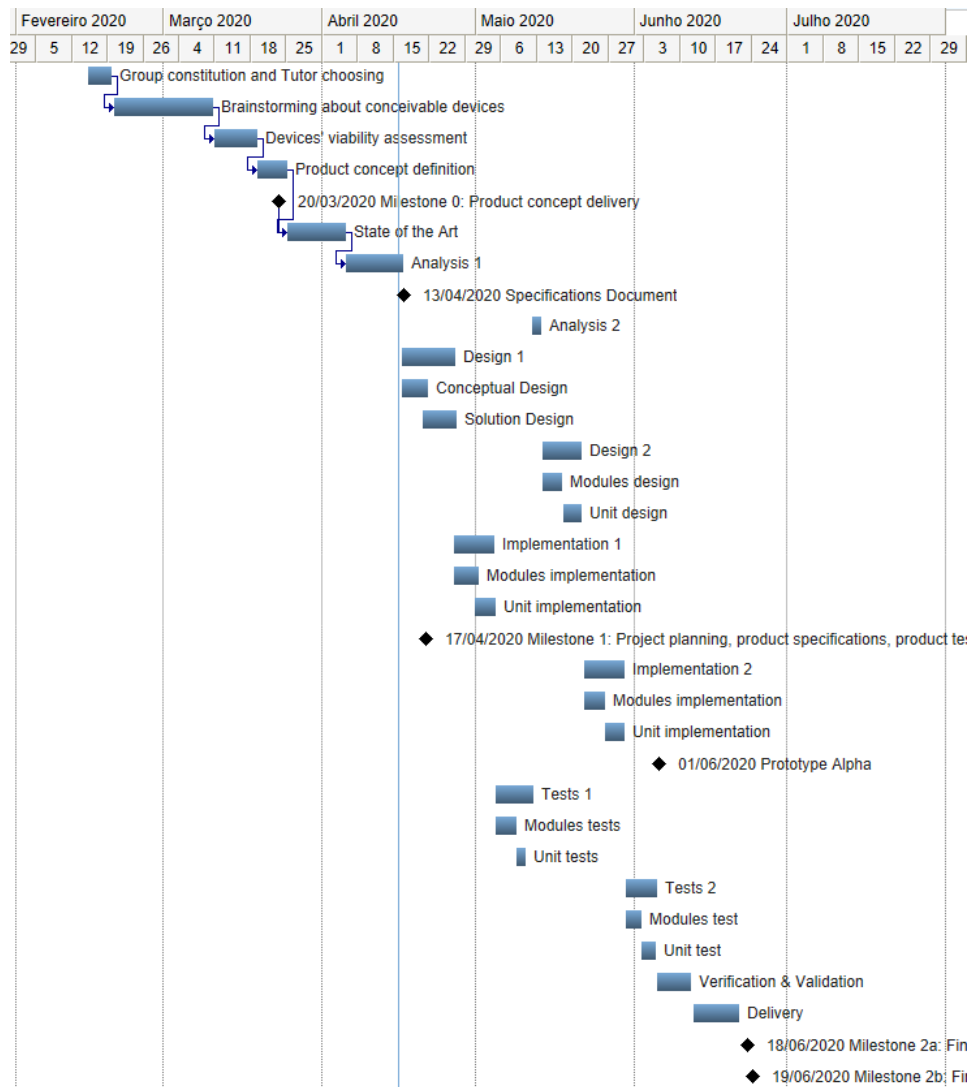


Figure 2: Project planning: Gantt diagram 1

	Nome	Duração	Ínicio	Fim
1	Group constitution and Tutor choosing	3dias	14/02/2020	18/02/2020
2	Brainstorming about conceivable devices	57.13dias?	19/02/2020	09/03/2020
3	Devices' viability assessment	6.84dias?	09/03/2020	17/03/2020
4	Product concept definition	3.46dias?	17/03/2020	23/03/2020
5	Milestone 0: Product concept delivery	1dia	20/03/2020	20/03/2020
6	State of the Art	9.55dias?	23/03/2020	03/04/2020
7	Analysis 1	6.63dias?	03/04/2020	14/04/2020
8	Specifications Document	0dia	13/04/2020	13/04/2020
9	Analysis 2	4.94dias	09/05/2020	10/05/2020
10	Design 1	31.08dias?	14/04/2020	24/04/2020
11	Conceptual Design	14.63dias?	14/04/2020	19/04/2020
12	Solution Design	19.5dias?	18/04/2020	24/04/2020
13	Design 2	22.67dias?	11/05/2020	18/05/2020
14	Modules design	11.46dias?	11/05/2020	15/05/2020
15	Unit design	10.25dias?	15/05/2020	18/05/2020
16	Implementation 1	23.55dias?	24/04/2020	02/05/2020
17	Modules implementation	14.13dias?	24/04/2020	29/04/2020
18	Unit implementation	11.63dias?	28/04/2020	02/05/2020
19	Milestone 1: Project planning, product specifications, product tests identification and initial design	43.13dias	03/04/2020	17/04/2020
20	Implementation 2	23dias?	19/05/2020	27/05/2020
21	Modules implementation	12.17dias?	19/05/2020	23/05/2020
22	Unit implementation	11.25dias?	23/05/2020	27/05/2020
23	Prototype Alpha	0dia	01/06/2020	01/06/2020
24	Tests 1	21.88dias?	02/05/2020	09/05/2020
25	Modules tests	12.05dias?	02/05/2020	06/05/2020
26	Unit tests	4.92dias?	06/05/2020	07/05/2020
27	Tests 2	17.67dias?	27/05/2020	02/06/2020
28	Modules test	9.21dias?	27/05/2020	30/05/2020
29	Unit test	8.38dias?	30/05/2020	02/06/2020
30	Verification & Validation	19.75dias?	02/06/2020	08/06/2020
31	Delivery	26.05dias?	09/06/2020	18/06/2020
32	Milestone 2a: Final product design, prototype development, specifications tests and documentation - Report	0.05dia	18/06/2020	18/06/2020
33	Milestone 2b: Final product design, prototype development, specifications tests and documentation - Presentation	0.33dia	19/06/2020	19/06/2020

Figure 3: Project planning: tasks

4.1.2 Maximum Load

As mentioned in Section 2.7, the maximum load can be defined for the minimum velocity (safe motor operation) and for maximum power consumption increase. Thus, two alternative definitions, and consequently, tests arise for the maximum load determination:

1. maximum load (at minimum velocity): maximum load the vehicle can carry safely at the minimum velocity defined.
2. maximum load (at 50% over the mean power consumption): maximum load which causes a 50% increase in the mean power consumption, i.e., while operating at mean velocity.

To test the former, load should be increased slowly, measuring the vehicle mean velocity, until the minimum velocity defined is achieved. To test the latter, load should be increased slowly, measuring the power consumption, until a 50% increase over the mean power consumption is detected, while operating at the mean velocity.

The maximum load can then be defined as the minimum one the vehicle can carry while observing both criteria.

4.1.3 Autonomy

The autonomy is related to product's power consumption and the capacity of the battery chosen. Under the present abnormal circumstances is not reasonable to expect the product's power consumption to match the real one, thus, for all purposes, this will be considered as the one drawn by the car module itself, namely, the installed motors and sensors.

Then, the autonomy can be measured as the time interval between battery fully charged and safely discharged (the car stops), by fixating the car to a supporting structure with free moving wheels, and imposing the aforementioned conditions in Section 2.3.

4.1.4 Velocity

The vehicle must be operated within a safe range of velocity, as mentioned in Section ???. It is important to define these boundaries as follows:

- minimum velocity: minimum velocity defined for the vehicle, which must be attained even in the condition of maximum load. This value must be selected to assure safe motor operation.

- maximum velocity (no load): maximum velocity for the vehicle in the absence of an external load. This is the absolute maximum velocity for the vehicle.
- maximum velocity (maximum load): maximum velocity for the vehicle in the presence of the maximum load. This value must be selected to prevent excessive power consumption and motor overheating.

The aforementioned velocities should be tested in the designed conditions, within a sufficiently long distance to assure velocity reach and stabilization, and compared to the ones provided in the foreseen specifications.

4.1.5 Safety

As mentioned in Section ??, safety can be analysed in two ways, considering the preservation of people and goods.

To test human safety, it is important to identify the interactions between the user and the product, and which are the most prevalent and dangerous. Even so, the exhaustive test is outside the scope of the present work; a small set of features will be tested accordingly to the devised user manual, containing the safety measures. For example, battery installation and conditions should be tested, eventually leading to the posterior incorporation of safety measures in the product.

To test goods safety, it is reasonable to assume the operating conditions of the vehicle. Under these it is important to consider the most critical ones that concern the moments when the vehicle is left to be controlled locally, instead of user controlled operation. The critical conditions for local operations are divided into two sets:

- processing of user commands and vehicle operation: user commands can conflict with safety measures and, thus, should be overridden locally.
- communication loss: the vehicle is left to odometric navigation, preserving the safety of people and goods.

To test these two scenarios, they should be replicated, observing the system response and tolerance.

4.1.6 Image acquisition

The vehicle is equipped with a camera to assist the user in its navigation, thus, requiring the following variables to be tested: frame rate, range, and resolution.

Frame rate To test frame rate, the user screen must be updated with the number of frames received from the camera per second and checked against the defined boundaries.

Range To test camera's range, an object must be captured at increasing distances, until the image resolution is lost.

Resolution The minimum resolution should be tested as providing the least amount of information required for the user, while minimizing data transfer and processing overhead.

4.1.7 Communication reliability

A communication is reliable if it guarantees measures to deliver the data conveyed in the communication link. As reliability imposes these measures, it also adds overhead to the communication protocol, which must be considered depending on the case. For example, for the devised product, an user command must be acknowledged to be processed, otherwise, the user must be informed; on the other hand, losing frames from the video feed is not so critical — user can still observe conveniently the field of vision if the frame rate is within acceptable boundaries.

Thus, given the critical nature of user commands issued, the focus will be on this communication link. To test the reliability dummy packets should be sent from the user platform to the vehicle and be acknowledged and parsed correctly.

4.1.8 Closed loop error

As mentioned in Section 2.11 the velocity, direction and distance to obstacles must be continuously monitored to ensure proper vehicle operation. The closed loop error must then be checked and tested for these three variables, as the difference between reference (setpoint) and output (real) values, and comparing them to the specifications.

4.2 Validation tests

The validation tests should be performed by the client using the product's manual, so it is expected that a user without prior experience with the product should be able to use it correctly and safely. On the present abnormal circumstances, with limited access to the physical modules, specially for an

external agent, the validation is severely limited. Thus, it should be limited to user interface validation.

For this purpose, an external agent will be provided with the software application and the respective installation and usage manuals, and the feedback will be collected and processed to further improve the product.

5 Initial design

Following an analysis of the product's family tree (remote controlled cars), the state of the art and the QFD matrix in fig. 1, an initial design of the product itself can be produced (fig. 4). The selected approach was top-down, in the sense that the requirements and specifications were addressed and that resulted in a general diagram of the product concept. Some macro-level decisions were made in this stage to narrow the problem's solutions pool, as follows:

- The car itself should be battery-powered, as it is a free-moving object that is intended to work in environments where trailing cables could interfere with its regular movement.
- The device used to control the car should ideally be one already owned by the user, with an integrated screen (e.g. smartphone), as it would make it more affordable and have a more straightforward interface.
- The protocol for communication between the controlling device and the Rover should be chosen from within the pool of those readily available to smartphones (e.g. Wi-Fi, GPRS) to keep the price of the overall product down and make it as practical as possible.
- The control and communication unit for the car should be divided into two modules: one which can interface directly with the camera module and manage data transmission and reception at the applicational level of the TCP/IP protocol stack, with enough throughput for the specified video resolution and framerate. And another one which can measure and process sensor inputs and control the actuators in real-time.

Thus, summarising, the initial design yields the system illustrated in fig. 4, comprised of:

- **Raspberry Pi:** Interfaces with the camera directly, transmitting the information it receives to the smartphone. Receives user commands and sends sensorial information back to it;

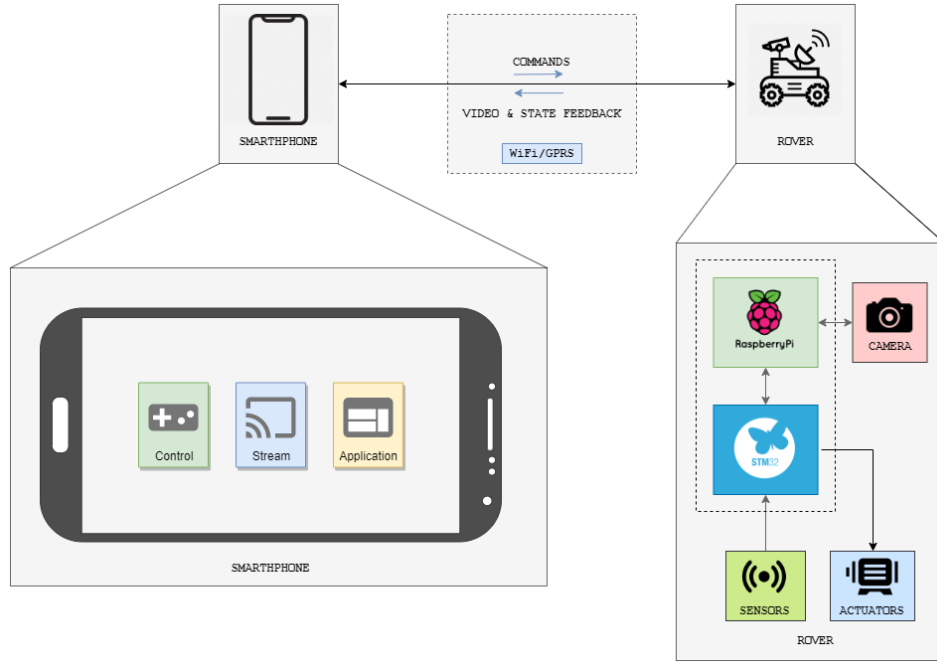


Figure 4: Initial design: Block diagram view

- **STM32:** Sends sensorial information to the Raspberry Pi module and receives commands from it. Controls the actuators according to the given instructions and sensor readings;
- **Actuators:** DC Motors that control the car's movement and head-lights for nocturnal or low light conditions;
- **Sensors:** Odometric sensors that supin this senseport the detection of obstacles and luminosity sensors;
- **Camera:** Device connected to the Raspberry Pi that allows the live stream of the car's surrounding environment;
- **Smartphone:** Grant visual feedback from the camera's live feed also allowing the user to control the movement of the vehicle intuitively;

Due to the extraordinary conditions imposed by the recently enacted confinement measures, the need rose to create a non-physical connection between both modules of the Rover. For that purpose, a network comprised

of two computers communicating over a TCP/IP connection served as the intermediary, one being the Raspberry Pi module and another being a computer connected to the STM32 module via RS232 (fig. 5)

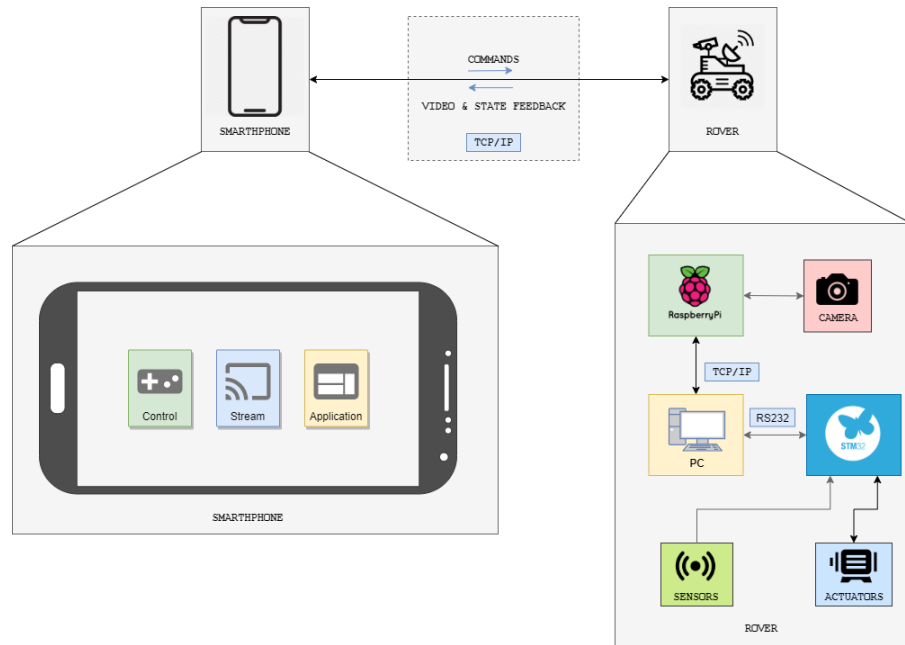


Figure 5: Initial design: Block diagram view considering the extraordinary conditions