Joint DLR / NASA Design Challenge 2020

CITY-DEL

YOUR COMPANION FOR URBAN LAST MILE DELIVERY

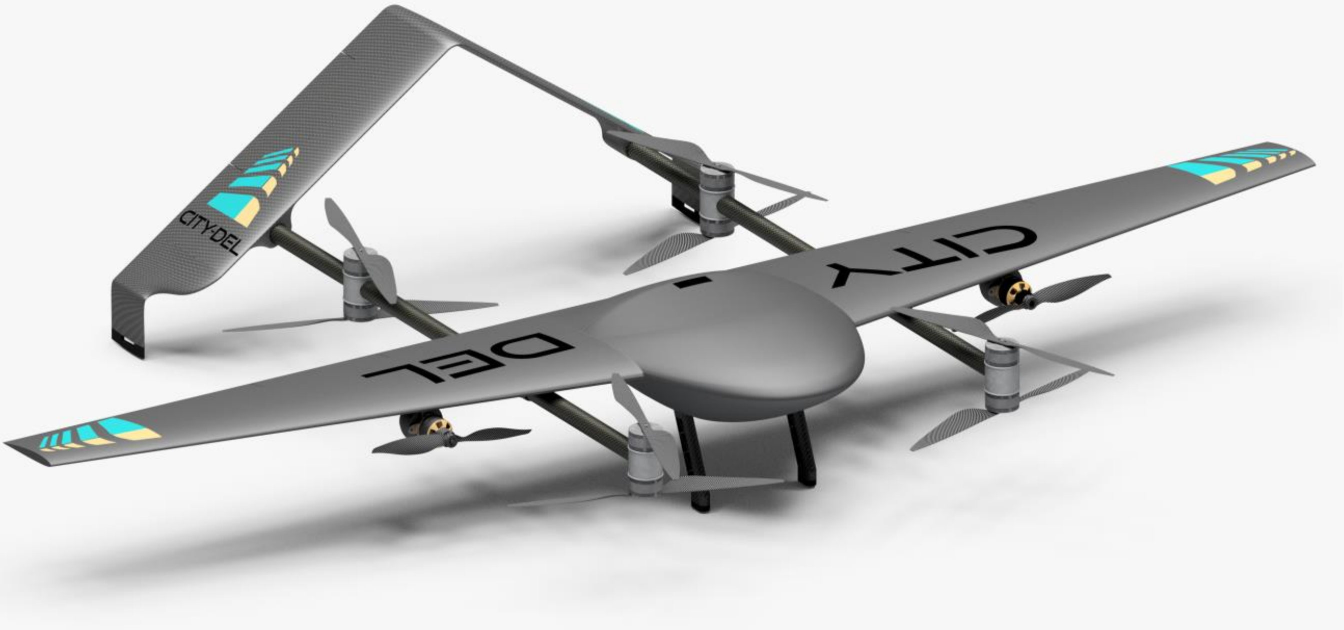
Team

Sören Bähr (TL)	Lenard Barkow
Jannik Herrmann	Neermegha Mishra
Sofia Schäfer	Rakshith Sudarshana

Academic Support

Prof. Dr.-Ing. Volker Gollnick

M.Sc. Jens Thöben



TUHH
Hamburg University of Technology

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ILT
Institut für
Lufttransportsysteme

TUHH
Technische Universität Hamburg

ILT
Institut für Lufttransportsysteme

TUHH, Institut für Lufttransportsysteme, D-21079 Hamburg

Institut für Lufttransportsysteme
Prof. Dr.-Ing. Volker Gollnick
Blohmstr.20
D-21079 Hamburg

Datum und Zeichen Ihres Schreibens	Geschäftszeichen	Hamburg,
	Prof. Dr.-Ing. Volker Gollnick	13. Juli 2020

Bescheinigung und Freigabe des Beitrags zur DLR/NASA-Design- Challenge 2020

Hiermit wird bescheinigt, dass der Beitrag der Studierenden zum Studierendenwettbewerb DLR/NASA-Design-Challenge 2020 am Institut für Lufttransportsysteme geprüft und freigegeben wurde. Die Einreichung des Beitrags wird hiermit befürwortet.
Für weitere Rückfragen stehen Herr Jens Thöben, M.Sc. jens.thoeben@tuhh.de oder ich gerne zur Verfügung.

Mit freundlichen Grüßen

Volker Gollnick

Volker Gollnick
Institutsleiter

Postanschrift
21071 Hamburg

Besucheranschrift
Blohmstraße 20
21079 Hamburg

Telefon
+49 (0) 40 428 78-4196

Fax
+49 (0) 40 428 78-2979
www.tu-harburg.de/ilt

E-Mail
volker.gollnick@tu-harburg.de

TUHH
Technische Universität Hamburg

ILT
Institut für
Lufttransportsysteme

TUHH, Institut für Lufttransportsysteme, D-21079 Hamburg

Institut für Lufttransportsysteme
Prof. Dr.-Ing. Volker Gollnick
Blohmstr.20
D-21079 Hamburg

Datum und Zeichen Ihres Schreibens	Geschäftszeichen	Hamburg,
	Prof. Dr.-Ing. Volker Gollnick	13. Juli 2020

Bestätigung der eigenständigen Projektbearbeitung zur DLR/NASA-Design-Challenge 2020

Hiermit wird ausdrücklich bestätigt, dass

Herr Sören Bähr, TUHH
Herr Lenard Barkow, TUHH
Herr Jannik Herrmann, TUHH
Frau Neermegha Mishra, TUHH
Frau Sofia Schäfer, TUHH
Herr Rakshith Sudarshana, TUHH

den eingereichten Projektbericht sowie alle dahinter liegenden Arbeiten vollständig eigenständig und ausschließlich unter Zuhilfenahme der angegebenen Quellen erstellt haben. Für weitere Rückfragen stehen Herr Jens Thöben, M.Sc. jens.thoeben@tuhh.de oder ich gerne zur Verfügung.

Mit freundlichen Grüßen

Volker Gollnick

Volker Gollnick
Institutsleiter

Postanschrift
21071 Hamburg

Besucheranschrift
Blohmstraße 20
21079 Hamburg

Telefon
+49 (0) 40 428 78-4196

Fax
+49 (0) 40 428 78-2979
www.tu-harburg.de/ilt

E-Mail
volker.gollnick@tu-harburg.de

Abstract

The City-Del drone concept fulfills the requirements for an unmanned aerial vehicle for package deliveries within urban areas as part of the Joint Nasa/Dlr Aeronautics Design Challenge 2020. This project gives an overview of the current situation in this sector, including fundamental challenges and needs like environmental challenges due to noise emissions. The City-Del drone is built entirely of carbon fiber reinforced polymer to minimize the weight and thus the necessary thrust to lift the aircraft. To operate in confined spaces, the aircraft holds two modes, a vertical mode and a horizontal mode. The vertical mode is provided through 8 coaxially arranged rotors resulting in a four point configuration, which creates the necessary thrust to climb and descent. This gives the City-Del drone maneuverability. The horizontal mode is provided with two rotors mounted on the wings and an inverted V-Tail. Due to a strong aerodynamic performance the aircraft has a low drag coefficient and at the same time a good lift coefficient, resulting in an excellent glide ratio. During the mission, a battery pack consisting out of 60 cells supplies the engines and avionics with sufficient electrical power. As a novelty for UAVs the City-Del holds a capacitor, which bypasses the energy supply during the battery and packages replacement. Based on the City-Del concept, mandatory operations and possibilities are presented. Furthermore, the costs are estimated, which are comparably low for a UAV of this magnitude. This results in better profitability for logistics companies.

City-Del Team

Sören Bähr (TL)

8th Semester Bachelor Mechanical Engineering

Lenard Barkow

2nd Semester Master Aircraft Systems Engineering

Jannik Herrmann

2nd Semester Master Aircraft Systems Engineering

Neermegha Mishra

6th Semester Microelectronics Engineering and Microsystems

Sofia Schäfer

2nd Semester Master Aircraft Systems Engineering

Rakshith Sudarshana

6th Semester Mechanical Engineering and Management

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Nomenclature

Formula Symbols

Latin

Symbol	Unit	Meaning
C	m	Chord
c	m/s	Speed of light
d	m	Distance
E		Glide ratio
g	m/s^2	Acceleration of gravity
K	-	Efficacy factor
L	N	Lift
l	m	Lever arm
M	N	Torque
m	kg	Mass
p	Pa	Pressure
S	m	Lift producing area
s	m	Wingspan
t	s	Time
v	m/s	Velocity
W	kg	Weight

Greek

Symbol	Unit	Meaning
α	deg	Angle of attack
γ	deg	Angle between horizontal and empennage
ρ	kg/m^3	Density
μ	Pa $\cdot$ s	Dynamic viscosity
ν	m^2/s	Kinematic viscosity

Subscripts

Subscript	Meaning
AC	Aircraft
b	Body
D	Drag
d	Distance
E	Elevator
her	Horizontal engine and rotor unit
L	Lift
l	Length
R	Rudder
ref	Reference
t	Time
ver	Vertical engine and rotor unit
vt	V-Tail empennage
W	Weight
w	Wing

Abbreviations

5G	Fifth Generation Cellular Network Technology
ABAS	Air Based Augmentation System
A/C	Aircraft
AoA	Angle of Attack
B2B	Business-to-Business
BVLOS	Beyond Visual Line of Sight
CEP	Courier, Express and Parcel
CFRP	Carbon Fiber Reinforced Polymer
COG	Center of Gravity
DAA	Detect and Avoid
GALILEO	European Global Navigation Satellite System
GBAS	Ground Based Augmentation System
GLONASS	Russian Global Navigation Satellite System
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HQ	Headquarters
IMU	Inertial Measurement Unit
IR	Infrared
LED	Light Emitting Diode
MSL	Mean Sea Level
NW	Network
ROC	Rate of Climb
ROD	Rate of Descent
SAM	Served Addressable Market
SBAS	Satellite Based Augmentation System
SIM	Subscriber Identity Module
SOM	Serviceable Obtainable Market
TAM	Total Addressable Market
T/O	Takeoff
TOF	Time of Flight
TWR	Thrust-to-weight Ratio
UAV	Unmanned Aerial Vehicle
UTM	Unmanned Drone Traffic Management System
VTOL	Vertical Takeoff and Landing

1 Introduction

State of the art. Transportation of people and goods is a growing problem in most of the urban areas around the globe. According to the United Nations, more than 50 % of the population worldwide live in urban areas and this number is expected to increase to 68 % by 2050 [13]. An increase in urbanization and the number of vehicles on road and expansion of the economy and single package delivery due to the rise of internet-based purchasing have led to congestion in urban areas [24]. A large proportion of congestion on roads is due to urban freight logistics and the roads of historic cities in Europe were not designed to furnish the growing demand of 21st century [4]. Moreover, an increase in fuel price and a decrease in air quality by CO_2 emissions has challenged governments and city management to search for alternative solutions without disturbing the needs of people. Unmanned aerial vehicle (UAV) is an emerging technology that has found its application in many fields, grabbing the attention from start-ups to big-league companies. One such application of an UAV could be to act as a part of a solution for delivering goods in urban areas.

Objective. The NASA/DLR AERONAUTICS DESIGN CHALLENGE 2020 is to develop an autonomous unmanned aviation system capable of delivering packages up to a maximum weight of 2.50 kg and accomplish operation of two independent flights within a 15 km radius in inner city areas. This report details on the development of technical and business aspects of the new CITY-DEL drone, providing Business-to-Business (B2B) solutions for the current urban mobility problems by offering improved delivery time, reduced expenses and zero emissions [7].

Design guidelines and requirements. This section gives a brief overview of the demanded features of the UAV. A complete list of requirements can be found in the appendix B1.1.
The main task is to design a safe, reliable, profitable and low-noise emitting autonomous unmanned aircraft (A/C) with continuous communication, navigation and collision avoidance capability. This aircraft is supposed to deliver small packages via air transport to designated landing platforms. Those platforms are also an important part of the concept and need to be outlined with the relating required ground systems. The maximum size of these platforms is 7.50 m × 15.00 m. The package has a maximum weight of 2.50 kg and a maximum size of 15 cm × 15 cm × 15 cm. The required distance that needs to be covered by the UAV is 15 km and has to be reached in at least 20 min. The flight to the destination is referred to as a *mission*, whereas the returning flight to the home base does not belong to it. However, the aircraft needs to cover at least 30 km with its battery before reloading with the second package at the home base or logistics headquarters (HQ). Only after two completed missions, human intervention is allowed. During the mission, the UAV must fly in heights between 120 m and 150 m. An altitude of 120 m needs to be reached within a radius of 1500 m. Further it must be able to resist rainy weather conditions (snow and ice excluded) as well as winds up to 20 kn (37 km/h). Additionally to the aircraft design, a solid business plan needs to be developed for this purpose.

CITY-DEL. All the requirements named above were included in the design of the UAV by the company named CITY-DEL. The approach of the design process, the required sensors for the UAV and the evaluation of the business scenario will be discussed in the chapters below.

2 Design Process

The following chapter gives a detailed overview of the technical design of the City-Del drone. The approach of designing an UAV that meets all the given demands can be followed successively in the subsections.

2.1 Concept

To work as a team effectively, a project plan was defined that includes the following steps: research, concept freeze, CAD freeze, simulation freeze, and documentation. Due to a weekly virtual meeting, it was possible to stay informed about the progress of the project consistently, and the team members were able to discuss problems that had to be solved.

As a methodical approach, a morphological analysis was chosen to compile ideas regarding the main functions of the vehicle. The main functions were derived from the Nasa Aeronautics Design Challenge criteria. The functions can be divided into takeoff (T/O) and landing, propulsion, package carrier, home base procedure, and landing gear. Each team member collected potential solutions for the functions listed above to maximize the alternatives of the design. In the end, the concepts were evaluated, and the best option was chosen in a team discussion. The result of this methodical approach is a design that all members developed conjointly.

2.1.1 Aircraft

After choosing the main features in the morphological analysis, this section gives a general overview of the aircraft. It is a hybrid of a fixed-wing concept with an inverted V-tail combined with a multi-copter characterized by the following properties:

- 8 rotors for vertical drive guarantee a low probability of failure and a fast climbing rate
- 4 point configuration with redundant coaxial rotors
- 2 rotors for horizontal drive placed on the front of the wings to achieve a high cruise speed
- no need for a runway due to vertical takeoff and landing (VTOL)
- low structural weight through lightweight materials and sandwich constructed wings
- down facing V-shaped tail for horizontal and vertical stability and maneuverability
- package protection given by the body structure on all six sides
- package delivery with a hatch mechanism on the bottom
- high lift-to-drag ratio because of an aerodynamic wing design
- replaceable package carrier unit in order to achieve fast processing on the ground
- high wing configuration allowing a small landing gear and low vertical movement of the package

A three side view can be seen in figure 2.1.

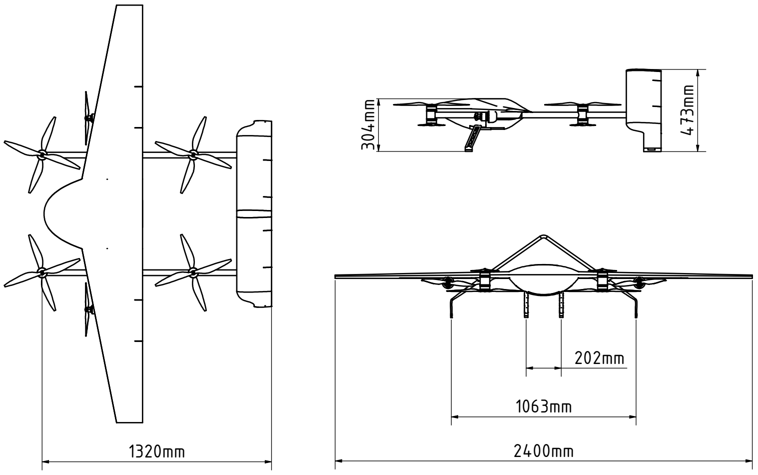


Figure 2.1: Three side view of the City-Del drone

2.1.2 Home Base Procedure

The home base is located at a logistic headquarters. The procedure consists of four steps: landing on the conveyor belt, alignment, exchange of battery and package refill and the takeoff.

The principle of the home base relies on a conveyor belt where the UAV lands. The drone needs to be adjusted towards the direction of the conveyor belt. The aircraft is carried into a headquarter while getting aligned and fixed in position by a rail-guided system. A defined position is indispensable for a reliable change of the package carrier unit. The A/C moves along on the conveyor belt to a robot arm exchanging the package carrier unit together with the battery pack. During this process, the energy supply is bypassed by a capacitor. In the end, the drone is carried outside of the logistics building, where it is ready for T/O to deliver the next package. This turnaround process can be accomplished in under 2 minutes. An overview of this concept is given in figure 2.2.

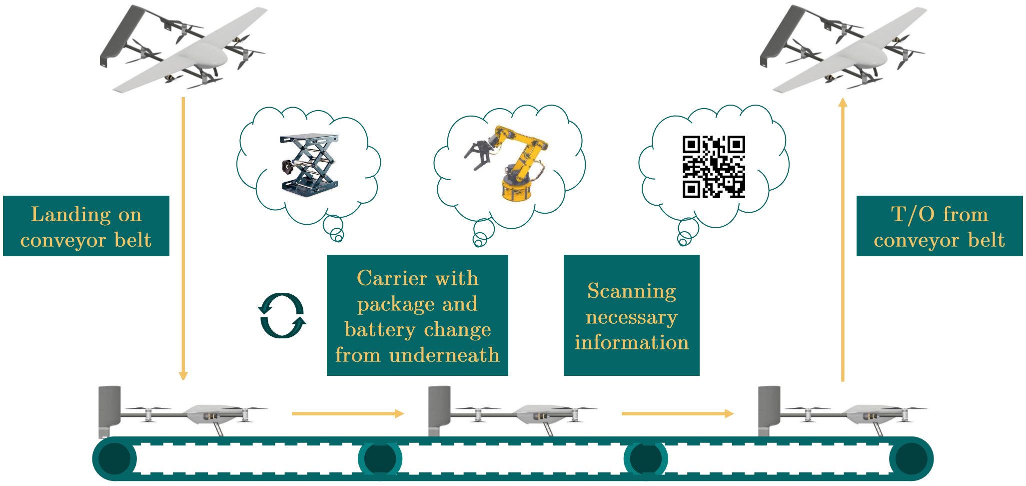


Figure 2.2: Home base procedure

2.1.3 Landing Platform

After placing an order, the customer receives a short message right before the drone starts the delivery and thus knows that within the next 20 minutes, the package will arrive. Nevertheless, for a safe landing, the following conditions need to be assured: the platform needs to be equipped with components, that send signals to identify the A/C. This guarantees a precise landing on the platform. If the drone is about to land, a minimum space of 4.50 m × 4.50 m is demanded to ensure navigation process.

The landing process is facilitated of two components to help the landing platform to connect with the UAV. For the identification process an array of infrared (IR) light emitting diodes (LED), *MarkOne Beacon*, is kept on the landing platform while the other part, an IR camera, the *IR Lock sensor*, is attached to the A/C's body, facing downward [31]. A detailed overview of all sensors used can be found later in chapter 3. After the components connect, the A/C safely lands on the mat through the camera's sensing capability. It focuses only on IR rays, which simultaneously increases the reliability for precise landing [31]. This process is illustrated in figure 2.3. On the mat, the A/C drops the delivery and quickly returns to the logistic headquarters. Afterwards the customer takes the package and removes the mat.

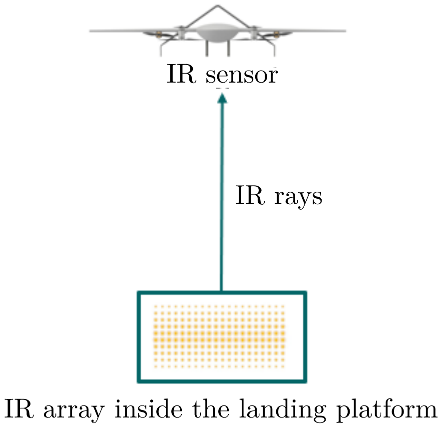


Figure 2.3: Identification of the platform

2.2 Mission Analysis

Based on the list of requirements, a mission profile is established to get a first impression of the boundary conditions that need to be fulfilled. With the analysis of the mission, it is possible to develop a design of the A/C that covers the high demands.

The decision to use a VTOL and the given time for a mission leads to estimated time for the horizontal and vertical mission phase. A mission begins with taking off at the home base and ends when the A/C lands safely at the costumers' landing platform. The maximum range that the drone needs to cover is 15 km in 20 minutes. For the takeoff as well as for the landing process, the first estimation of one minute is considered, so that the cruise flight has to be completed in 18 minutes. In an ideal case, a rate of climb of at least 2 m/s is required to reach a height of 120 m in roughly one minute. Due to the fact that weather conditions can differ from mission to mission, additional time for unforeseen eventualities like wind or rain should be considered. Furthermore, gaining height takes longer than decreasing, but in exchange unloading the package from the drone is time intensive. This is why those two phases are considered to be similar for a first estimation of the mission.
To cover a distance of 15 km during the mission cruise in a maximum of 18 minutes, the A/C should be able to reach a velocity of at least 50 km/h. Taking the given wind velocity from the requirements into consideration, the demanded velocity of the drone accumulates to 87 km/h. For the following calculations, the rechargeable battery pack is assumed with 90 % of the capacity. Those 90 % need to be sufficient for the mission, as well as for the flight back to the home base. The remaining 10 % of the available capacity are assigned to a power backup and spares the batteries for longer life.

2.3 Propulsion

After analyzing the mission, the next step is to determine a propulsion concept. This step of the designing process relies on the established aviation software eCalc [27]. The goal is to find corresponding rotors and engines with fitting battery and controller. This is a highly iterative process. In order to begin at a reasonable point, some assumptions need to follow. The approach of the propulsion concept is based on a way to early mass estimation. The weight is considered with a safety factor to find the upper mass limit, which ensures that the propulsion concept works for the designed UAV. The assumed values are summarized in table 2.1.

Table 2.1: Early mass estimation

Component	Weight
Battery	4.00 kg
Rotor and engine	2.50 kg
Avionics hardware	0.50 kg
Structure	2.50 kg
Package	2.50 kg
	12.00 kg

According to this estimation the rotors need to generate at least 12 kg of thrust to be able to take off. To achieve a good rate of climb and maneuverability a thrust-to-weight ratio of 1.5 to 2 is recommended for drones [47].

2.3.1 Design with eCalc

Because of the hybrid design, the flight characteristics of the aircraft are divided into two modes: vertical flight as a multicopter and horizontal flight as a propeller-driven airplane. Those are computed separately in eCalc in order to fulfill the different mission requirements. The operation of the UAV is supposed to take place in urban and suburban areas in Europe, as mentioned in chapter 6 regarding the business case. This leads to the assumption of an airfield altitude of about 500 m above mean sea level (MSL). This documentation focuses on the urban area case due to the fact that European cities usually do not exceed 500 MSL [38].

However, further calculations in eCalc show that for higher operating areas up to 2500 MSL the A/C is still be able to fulfill the requirements (see appendix B2.1). To guarantee a delivery all year long the equipment of the UAV was calculated for 0 °C temperature. Harsh weather conditions do not cause any problems for the drone, meaning that the dimensioning of the UAV was calculated for the worst case scenario.

For the calculation in horizontal mode, preliminary considerations resulted in a wing area of 50 dm^2 and a frontal area of 10 dm^2. Several iteration steps led to a combination of propellers and engines with corresponding battery and controller that interact in a way that the A/C is able to meet all mission requirements. This process was dynamic throughout the project because the values changed as soon as one component was adjusted, added or removed. Table 2.2 shows the main properties of the components at maximum power. To reach a total battery capacity of 50 000 mAh and a voltage of 22 V six batteries are connected in series with ten in parallel.

Table 2.2: Overview of the mission and return home at max. power (0 °C and 500 MSL)

	Property	**Mission**	**Return**	**Unit**
General	Takeoff weight	11.72	9.22	kg
	Battery capacity	52.00	38.00	%
Vertical	Rate of climb	3.20	4.80	m/s
	Flight time	1.60	1.60	min
	Battery usage	12.00	8.00	%
	Thrust-to-weight ratio	1.60	2.00	–
	Max. current	25.53	23.79	A
	Max. voltage	20.58	20.58	V
	Max. rotational speed	5000.00	5000.00	1/min
Horizontal	Stall speed	72.00	72.00	km/h
	Max. speed	126.00	126.00	km/h
	Flight time	14.00	14.00	min
	Battery usage	40.00	30.00	%
	Max. current	42.86	42.86	A
	Max. voltage	21.00	21.00	V
	Max. rotational speed	11 902.00	11 902.00	1/min

Regarding the values listed in table 2.2 the time for the takeoff and landing procedure at maximum power (worst case scenario) is lower compared to the first estimation in the mission analysis.However,the aircraft has a higher rate of climb (ROC), so the planned time is still sufficient. The A/C reaches a top horizontal speed of 126 km/h. Regarding the mission analysis (see section 2.2), the required velocity can be achieved. Based on the worst case scenario, where flying against the maximum wind velocity is assumed, the maximum thrust and 40 % of the battery in cruise operation is used. The battery would last 14 minutes and the A/C could cover a distance of 20.76 km. This distance outreaches the requirements of 15 km given in the introduction. Hence in an ideal cruise flight, the battery consumption can be reduced. To guarantee enough safety to not reach the stall speed the lower limit is set to 86.40 km/h, which gives 20 % safety before stall effects occur.
For a transfer from vertical to horizontal flight (transition phase), a time of 10 s was considered, in which the thrust of the horizontal engines is increased and the thrust of the vertical engines can be lowered. In the transition phase the stall speed needs to be reached before the vertical engines are turned off.
Summarizing the above the A/C is able to meet all the requirements regarding the flight mission. The main mission characteristics with the selected values are shown in figure 2.4.

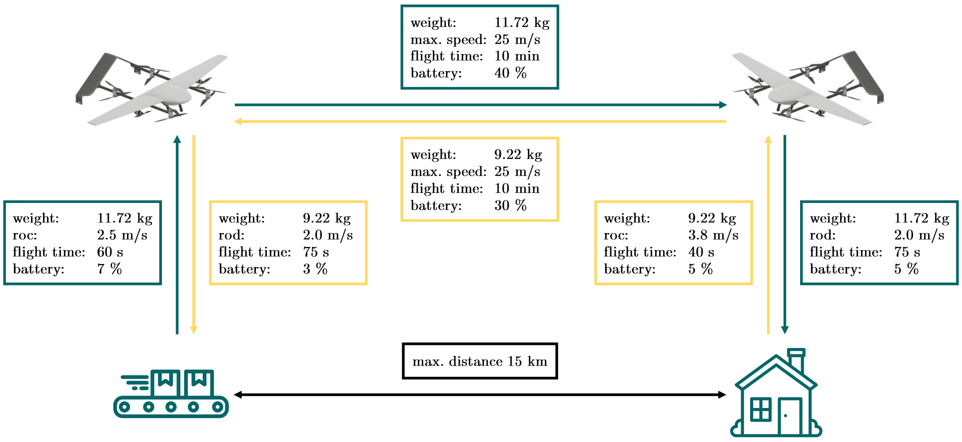


Figure 2.4: Intended mission values

2.4 Weight and Balance

After determining the hardware with the help of eCalc a more accurate mass estimation has to follow. Because of new weight values, another calculation has to be made in eCalc. After several iteration steps the appropriate parts were specified, to obtain the values discussed earlier in section 2.3.1. In the following examination, a complete component list is shown with their quantity and weight. With this information the center of gravity (COG) can be determined.

2.4.1 Mass Estimation

As a first step the sensors and power components for the UAV were selected before the calculations, because the avionic parts can be chosen without additional information from other fields. Right after the components were defined, their weight was taken into consideration for the mass estimation. Most of the sensors are very lightweight and small. The heaviest parts of the electronic components are the batteries. Regarding the power requirements for the A/C a solution of 60 batteries of the same type was identified. Table 2.3 shows the corresponding avionic components and their weight. Further information on the avionics field is given in chapter 3.

Table 2.3: Component list and mass estimation avionics

Component	**Product Name**	**Quantity**	**Weight**
Battery	*LG INR21700-M50T* 5000 mAh	60	4080 g
Backup Battery	*1st BUFFER-Pack 3×50*	1	46 g
Controller	*Roxxy BL Controll 940-6*	10	470 g
Mainboard	*Pixhawk 4*	1	16 g
GPS sensor	*Pixhawk 4 GPS Module*	1	38 g
DAA	*TeraRanger Tower Evo - 60 m*	4	48 g
Distance sensor	*Terabee One*	1	10 g
Infrared sensor	*IR-Lock Sensor*	1	22 g
BVLOS modem	*Botlink XRD* for 4G/ LTE	1	20 g
Antenna	*Taoglas TG.30.8113 - A, II*	1	7 g
Antenna	*Taoglas FXUB66.01.0305C3*	1	7 g
Simcard	*O_2-SIM prepaid card*	1	4 g
			4768 g

The following table 2.4 summarizes type and weight of the engines and rotors that resulted from the eCalc calculations shown in section 2.3.1.

Table 2.4: Component list and mass estimation propulsion

Component		**Product Name**	**Quantity**	**Weight**
Vertical	Engine	*T-Motor V505-260*	8	1800 g
	Rotor	*T-Motor CF 19x6*	8	80 g
	Motor mount	Aluminium	4	170 g
Horizontal	Engine	*Scorpion S-4020-10 (630)*	2	610 g
	Rotor	*Graupner E-Prop 11x7*	2	16 g
				2676 g

To finally calculate the mass of the A/C, the components for the structure had to be identified. The chosen materials and corresponding weights are represented in table 2.5. To lower the production costs the used laminates are the same type, as well as the inner material of the sandwich construction.

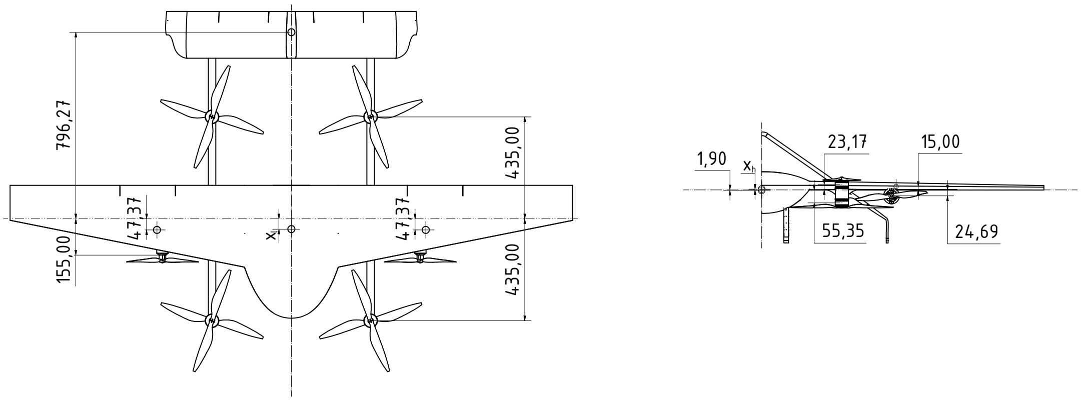
Table 2.5: Component list and mass estimation A/C structure

Component		Product Name	Quantity	Weight
Wing	Beam	*DPP™ CFK-Rohr D12×10×1,050*	2	102 g
	Foam	*ROHACELL® 51 HF*	2	350 g
	Laminate	*UNIPREG® Kohlegelege 100*	6	280 g
	Servos	*MKS 747 HV*	2	78 g
V-tail	Beam	*DPP™ CFK-Rohr D10×8×1000*	2	82 g
	Foam	*ROHACELL® 51 HF*	2	175 g
	Laminate	*UNIPREG® Kohlegelege 100*	3	140 g
	Servos	*KST DS225*	2	52 g
	Skid	Rubber Lining	2	20 g
Body	Laminate	*UNIPREG® Kohlegelege 100*	2	95 g
	Legs	*DPP™ CFK-Vierkant 40×20×150*	2	30 g
	CFRP Frame	*DPP™ CFK-Rohr D30×28×1200*	2	272 g
				1676 g

With the package weight of 2.50 kg and an additional weight of 0.10 kg to factor in cables and other connection components (in most components already included), the total mass of the A/C accumulates to 11.72 kg. This is a lower value compared to the first estimation that was made earlier in section 2.3. The results with the final components show that all requirements of the mission are fulfilled.

2.4.2 Center of Gravity

With the estimation of the weight being complete, the next step is to determine the center of gravity of the A/C. Because of the symmetry, only two coordinates are missing: along the length (top view) and the height (front view). The center of gravity for the body part can be influenced by the way the package, battery and hardware are sited inside the drone. During the design of the A/C the components were positioned in a way that the configuration inside the body balances out the center of gravity in the desired way. In the following, the representative calculations are shown with the final values. The coordinate of the center of gravity along the length of the A/C should be right in the middle of the vertical rotors so that there is no torque when all rotors are moving at the same speed for T/O and landing. The lever arms are displayed in a top view in figure 2.5a.



a) Lever arms along the length

b) Lever arms along the height

Figure 2.5: Lever arms of the A/C top and front view

To determine the distance to the center of gravity of the body the torques are added up. The corresponding equation is shown below (2.1):

$$\sum M_l = x_b m_b + 2 \cdot (-0.155) m_{her} + 2 \cdot (-0.04737) m_w + 0.79627 m_{vt} \overset{!}{=} 0 \tag{2.1}$$

This leads to a lever arm of the body of $x_l = 0.0440\,\mathrm{m}$. The same procedure for the coordinate along the height leads to equation 2.4.2 with the related lever arms displayed in a front view in figure 2.5b.

$$\begin{aligned} \sum M_h = x_h m_b + 4 \cdot (-0.05535) m_{ver} + 2 \cdot (-0.02469) m_{her} + \\ 4 \cdot (-0.02317) m_{ver} + 0.012 m_{vt} + 0.015 m_w \overset{!}{=} 0 \end{aligned} \tag{2.2}$$

In a ideal case, the center of gravity should have the same height as the contact point of the horizontal thrust laying underneath the wing. This leads to the body COG height of $x_h = 3.1946\,\mathrm{mm}$.

Summing up the above, the components inside the body should be located in a way that the center of gravity of the UAV has a ideal distance of 0.0440 m to the lateral axis and an ideal height of 3.1946 mm.

2.5 Aerodynamics

Regarding the overall concept with separated rotors for the vertical and horizontal thrust, the aerodynamic design will also be separated into two parts: wing and tail empennage. The main focus, however, will be the aerodynamic design of the wings. Therefore the free license program XFLR5 for 2D subsonic airfoil analysis is used [8]. It includes a NACA-airfoil generator with the option of defining flaps. Moreover, different 3D analysis tools are provided to investigate the aerodynamic performance of an aircraft. For the following examination, a 3D panel analysis was used.

2.5.1 Wing

The main task of the wing is to produce the necessary lift at cruise flight phase. Due to a chosen VTOL in multicopter mode no further considerations regarding the takeoff and landing are required.

Lift requirements. The required lift has to equal the weight of the drone. The general formula of lift is shown in equation 2.3 [36]:

$$L = \frac{\rho}{2} v^2 c_L S_{w,ref} \tag{2.3}$$

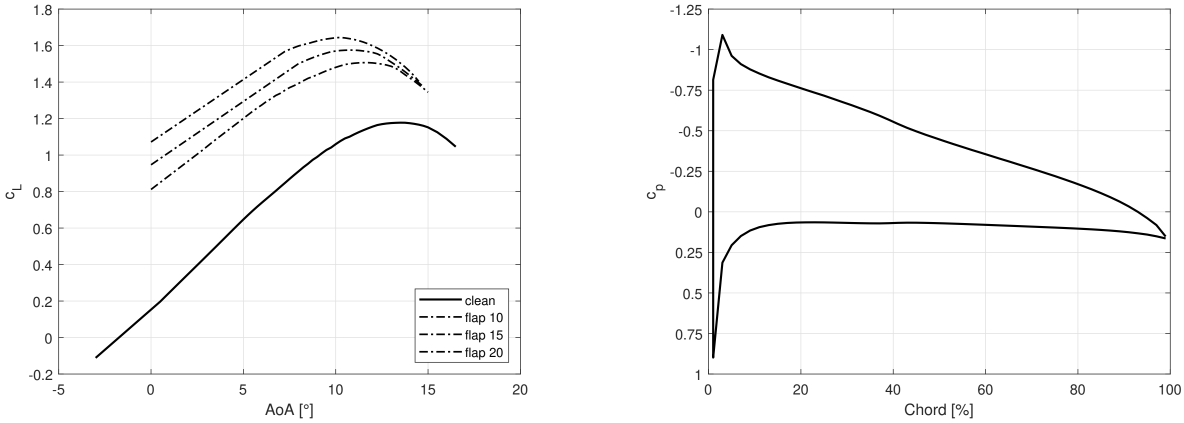
Taking the mass estimation into account a minimum lift for the drone can be calculated:

$$L_{min} \geq W = m_{AC} g = 114.97\,\mathrm{N} \tag{2.4}$$

Again, to guarantee enough safety to not reach the stall speed the lower limit is set to 86.4 km/h, which gives 20 % safety before stall effects occur (compare 2.3.1). To analyse the wings together with the body, a simplification of the body structure had to be made. With the equations 2.3 and 2.4 as well as $v_{min} = 86.4\,\mathrm{km/h}$, density $\rho = 1.225\,\mathrm{kg/m^3}$ and lift producing area $S_{w,ref} = 0.50\,\mathrm{m^2}$ a minimum lift coefficient of $c_{L,min} = 0.6518$ is required.

Profile selection. The profile of the wing defines the aerodynamic quality. The A/C is designed for low speeds, so the aerodynamic performance of the airfoils at 20 m/s to 35 m/s is dimensioning resulting in a REYNOLDS number with a range from 170 000 to 520 000. An airfoil suitable for the requirements is searched by comparing a few common airfoils from NACA. The NATIONAL ADVISORY COMMITTEE OF AERONAUTICS (NACA) provides a database of airfoils that were tested in wind tunnel. The four digits NACA-series was used for this process: the first digit designates the maximum chamber of the chord, the second digit describes the position of the maximum chamber and the last two digits indicate the the thickness of the chord [1]. The NACA-airfoil with 2 % of maximum chamber and 40 % of chamber position is selected and the thickness is increased until the lift coefficient meets the demands. Another important factor regarding the airfoil selection is a low drag coefficient to reach a high glide ratio. At a certain point, the airfoil thickness results in high drag coefficients when at the same time, only a little raise in lift coefficients can be determined. NACA 2410 is the thinnest airfoil that meets the requirements and simultaneously provides enough space to fit in the components. For the analysis with XFLR5 airfoils defined by 300 coordinate points were used.

Wing geometry. The operating area being within the city whereas at the same time a small landing platform is desirable, the wings should be kept as small as possible. Also, the package dimensions lead to a relatively small package carrier, thus small space for the wings to be attached is available. The body dimensions do not exceed 0.50 m, so a maximum chord of 0.35 m was chosen. To find a good balance between high lift coefficient and low wing span and to fit in all components for the wing structure a minimum chord of 0.15 m was determined. Those values are only qualitative characteristics of the wing and need to be examined in a more precise flow-analysis. In addition, the A/C is equipped with flaps to enable a rolling moment. The results of the 3D panel analysis with the chosen airfoil NACA 2410 as well as different angles of flap configurations are displayed in figure are shown in figure 2.6a. The distribution of pressure for an angle of attack (AoA) of $\alpha_{AC} = 4.50\,^\circ$ is displayed in figure 2.6b. This depiction shows that the nose of the wing produces a high suction. A general importance of the upper surface of the wing can be retraced, because of its pull effect along the chord resulting in lift. The bottom part of the chord generates an pressure overload, which is in this case comparably low. The reason for this unequal generation of under and over pressure is the relatively small chamber of the chosen airfoil. Moreover, a 3D display of the wing corresponding pressure distribution can be found in the appendix A2.1.



a) Lift coefficients

b) Pressure distribution for $\alpha_{AC} = 4.50\,^\circ$

Figure 2.6: Aerodynamic performance of NACA-airfoil 2410

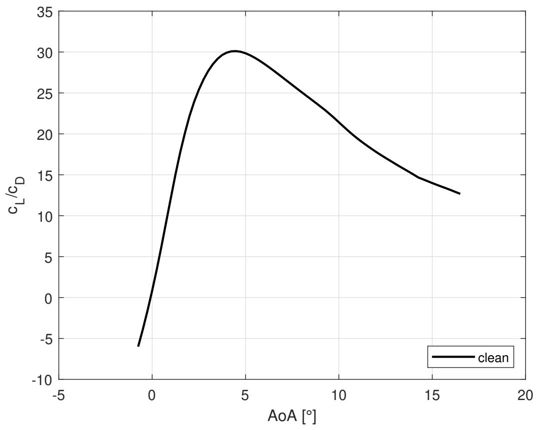


Figure 2.7: Glide ratio

Angle of attack and cruise speed. According to the lift requirements and figure 2.6a an angle of attack of $\alpha = 5.50\,^\circ$ is demanded. With this AoA being the highest used in flight, stall effects will not occur. In an ideal mission, the A/C operates with a cruise speed of $v_{AC} = 89\,\mathrm{km/h}$. On the one hand, the chosen cruise speed allows a better maneuvering of the drone to detect and avoid (DAA) any objects. On the other hand the battery usage is optimized when not flying at top speed. Recalculating the lift coefficient with v_{AC} lead to a $c_L = 0.6142$. As depicted in figure 2.6a this is achieved at an angle of $4.50\,^\circ$. As conclusion the wings are installed with $\alpha_{AC} = 4.50\,^\circ$. Moreover, this AoA induces a high glide ratio E, which is displayed in figure 2.7. Considering this, a distance of about 30 km can be covered by descending 1 km.

2.5.2 Tail Empennage

Usually, the elevator is used to adjust the equilibrium state of the aircraft. By bending the aircraft to the lateral axis, the AoA of the A/C is trimmed. The vertical tail is intended for direction stability. A V-tail is an unconventional arrangement of the empennage, where elevator and vertical tail are merged to one part. The main reason for the decision of a V shaped empennage is reducing the weight and induced drag of the A/C by having two rudders instead of three. This is possible because the two rudders are symmetrically arranged with an angle to the wings. Also, it is possible to use the down facing tail as a part of the landing gear. The disadvantage of a V-tail requiring longer runways does not apply to the City-Del drone, because it uses a VTOL. To simplify the design process, it is assumed that an used inverted V-Tail has analog physics to a normal one. To determine the geometry of the V-Tail a conventional empennage in T-configuration is computed in the first place. Therefore the area of the elevator and rudder can be computed with the equations 2.5 and 2.6 [18].

$$S_E = \frac{K_E C_w S_{w,ref}}{l_E} \tag{2.5}$$

$$S_R = \frac{K_R s S_{w,ref}}{l_R} \tag{2.6}$$

Those are combined to determine the V-Tail surfaces needed to ensure stability using the following equations 2.7.

$$S_{vt} = \frac{S_E + S_H}{K_E \cos^2(\gamma) + K_R K \sin^2(\gamma)} \tag{2.7}$$

$$\gamma = \tan^{-1}\left(\sqrt{\frac{S_R K_E}{S_E K_R K}}\right) \tag{2.8}$$

The angle γ is defined between the horizontal and the empennage with $\mathrm{K_E}$ $\mathrm{K_R}$ and K being assigned to as efficacy factors [34].

Table 2.6 summarized the geometry of the empennage taking into account that the inverted V-Tail is supposed to serve as landing gear and using a rectangular shape for simplicity.

Table 2.6: V-Tail geometry

Geometry parameter	Value	Unit
V-Tail area	0.17	m^2
Aspect ratio	2.15	–
Chord	0.20	m
Width	1.06	m
Opening angle	109	deg

2.6 Structure

For the success of a fast and safe delivery at the customer, the drone has to be lightweight and stable. The package has to be inside a safety carrier, protecting it from environmental influences.

To fulfill these requirements, a well considered A/C structure needs to be designed, that also serves as the connection between wings, V-Tail, body and the construction of the package carrier inside the body. Furthermore, a decent and stable way to land the drone needs to be realizable. For the following explanations, the corresponding parts are referred to with circled numbers. The figure for these numbers can be found in figure 2.8 below.

2.6.1 Body

The body ⑥ is located in the center of the drone and mainly contains the carrier with the package, battery packs, communication systems, sensors and the mainboard. They are divided into two sections: a permanent part including sensors, mainboard and communication systems in the upper half and a changeable part including battery and the package carrier in the lower half. Aiming for a lightweight design the structure of the body is made of carbon fiber. This material is also used for the pipes ⑤ that establish the connection between V-Tail and body. The pipes are also connected to the motors ⑪ via the motor mount part ⑩. Inside the pipes is a wiring harness for the electrical components.

2.6.2 Package Carrier

The package carrier's ⑱ main task is to lock the package and keep it safely, dryly, and without any impacts. The carrier is located inside the body of the drone. To align the package, a cage avoids jamming or tilting and ensures a reliable release at the customer. This is displayed in detail in the appendix B3.1.

In order to protect the package from pollution, the bottom of the carrier is closed by two hatches ⑰. The hatch-mechanism has a spring hinge, in order to close automatically. A permanent electromagnet on top of the carrier is used to hold the package in position by attracting an attached metallic stripe. When the permanent electromagnet turns off, the package is released and the hatches are opened by the package's gravity force. The spring hinges are constructed in a way that they open for a package weight over 200 g. Moreover, the hatches dampen the fall of the package from the height of 13 cm saving the package from taking damage. In an unlikely case of a power failure, the package would not drop out of the carrier, because of the permanent magnetic attraction. As mentioned in section 2.6.1 the package carrier is a changeable unit forming the bottom part of the drone's body. It has to be changed after every mission in the logistics headquarters to save time by avoiding recharges and package refills. After exchanging the whole unit, the drone is ready for T/O with a new delivery and fully charged battery in a few seconds. The removed unit is recharged in the logistics headquarters so it can be reused for another mission.

2.6.3 Legs

The landing system is set up by four landing points. Two carbon fiber legs ⑧ are on the left and right side of the package carrier. Two additional legs are on the endings of the V-Tail ③. The drone's weight of 11.72 kg is distributed on the four landing points, but theoretically every point is able to carry the whole weight of the drone on its own. The wide V-Tail creates a decent level of support and avoids tilting of the drone in every situation. Without using a landing gear, the drone has a slightly higher flow resistance coefficient, which is in exchange compensated by saving weight.

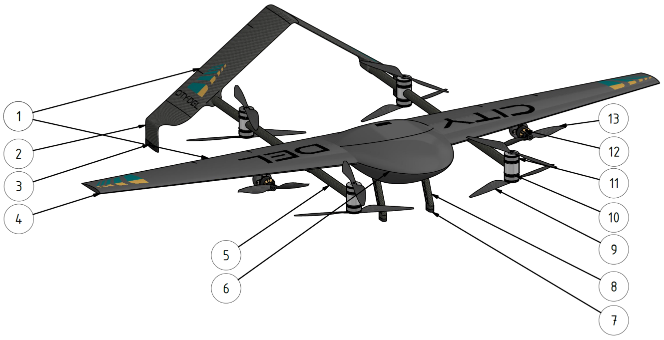


Figure 2.8: Positioning numbers oblique view

Table 2.7: Positioning numbers of parts

	Part
①	Flaps
②	V-Tail
③	Rubber Lining
④	Wing
⑤	Carbon Fiber Pipe
⑥	Body
⑦	Rubber Lining (Legs)
⑧	Carbon Fiber Legs
⑨	*T-Motor CF 19"*
⑩	Motor Mount
⑪	*T-Motor V505-260*
⑫	*Scorpion SII-4020-630*
⑬	*Graupner E Prop 11"*
⑭	*TeraRanger Tower Evo*-60 m
⑮	*Terabee One*
⑯	*IR-LOCK Sensor*
⑰	Carrier Flaps/ Spring Hinge
⑱	Battery and Package Carrier

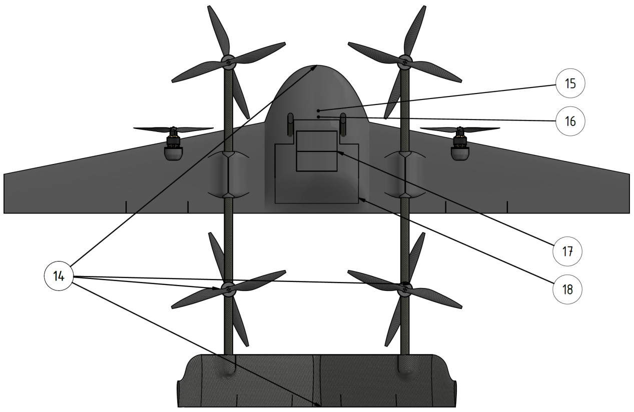


Figure 2.9: Positioning numbers bottom view

3 Avionics and Autonomy

While bypassing the ground transportation system with A/C delivery service with the advantages of fast delivery, reduced human error and autonomous operation around the clock, the most important aspect to consider is to guarantee the safety of the people and the product during the operation, circumventing any impact and perpetuating transmission of data, command and control. The autonomous operation of the City-Del drone replicates the senses of human eyes to see and acquire data, brain to process the obtained data and mouth to communicate it with other people, through a combination of various systems. The configuration of these systems and the motivation behind the decided configurations are explained in this chapter.

3.1 Sensors

'A sensor is a device that measures physical input from its environment and converts it into data that can be interpreted by either a human or a machine' [26].

For the A/C to fly autonomously, not only the systems on board need to work properly, but they also need to accustom themselves with every slight change in the adjacent terrain in order to maintain a safe flight. To accomplish that target, a combination of sensors for diversified purposes is assembled on board, considering different aspects of the operation, as described below.

3.1.1 Navigation System

The A/C requires a navigation system to chalk out the path and to keep track of its position to guarantee that the decided path is being followed. The establishment of this feature in the A/C is made possible by the following combination of the systems.

Inertial Measurement Unit. As the name suggests, Inertial Measurement Unit (IMU) is used for the purpose of measuring and reporting the A/C's acceleration, angular rate and orientation using a combination of three different sensors - Accelerometers, Gyroscopes and Magnetometers, providing information for each of the three vehicle axes: pitch, roll and yaw.

- Accelerometers provide the information about the acceleration force that the A/C is put through, along with the tilt angle of the vehicle in a stationary position. Besides the acceleration data, it provides velocity, direction, altitude and its rate of change's data. Even the information of vibration faced by the A/C is obtained [19].
- Gyroscope detects the angular velocity over the axis, so it is possible to determine the rate of change of angle in pitch, roll and yaw. This information is censorious as it is used to provide firmness to the drone and halts it from wobbling. The obtained information ensures that the delivery A/C maintains the expected angle for a steady maneuver for the entire flight duration [19].
- Magnetometer gives the perception of the direction for the movement of the A/C through the data of the magnetic field it experiences and by analysing the angle of the A/C with respect to the magnetic north [19].

Alongside the above mentioned three sensors across the direction of roll, pitch and yaw, another sensor is used in the A/C to provide information regarding the altitude of the vehicle to increase the accuracy of information on the A/C's position, a Barometer. This sensor observes the atmospheric pressure data and transforms it to the altitude of the A/C [19].

Global Navigation Satellite System. This is a global system to provide timing, location and pace information utilising several Global Navigation Satellite System (GNSS) subsystems, which provide information for way-finding purposes to City-Del A/C as well. GNSS is the worldwide expression to cite all the satellite navigation systems, including GPS, GLONASS, GALILEO. The GNSS navigation system is structured combining the following segments [29]:

- Satellites and ground auxiliary system for preservation
- GNSS signal receiver in the UAV

- Augmentation systems
  - Air Based Augmentation Systems (ABAS): Process to inspect the probity of the received signal
  - Satellite Based Augmentation System (SBAS): Process to inspect precision, flow and obtainability of the information acquired
  - Ground Based Augmentation System (GBAS): Process to scrutinize signals received from Ground Base

GNSS works with the principle of calculating the position on the surface of the earth by measuring the information regarding the pseudo-distance of the A/C, from at least three known position satellites, where the presence of the information from a fourth satellite can provide the information on the altitude as well. The navigation operation using GNSS for the A/C can be seen in the figure 3.1 [29].

IMU alongside GNSS and barometer combines to be the navigation system for the A/C, being an essential module of the flight control system, offering the drone maximum command and solidity. For the said motive *Pixhawk 4* is utilised, where accelerometer, gyroscope, barometer and magnetometer are inbuilt [9], with an external GNSS sensor, accumulating to be the navigation structure for the A/C.

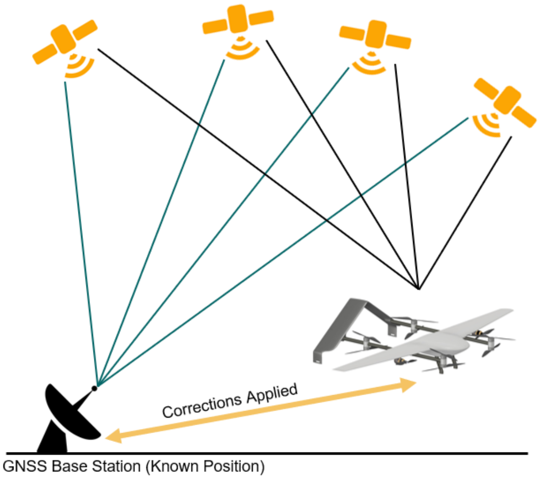


Figure 3.1: Navigation of A/C using GNSS

To avoid inaccuracy, the received signals from multiple satellites are integrated with the resulted signals from IMU and other sensors and sieved through Kalman filter to produce the evaluated data for position, speed, altitude for the A/C. The errors from the IMU are fed back to the mechanization equations block, which converts the measured acceleration, angular rate data from 'body frame to navigation frame' [16], to lessen the consequence of the errors, following the principle of 'Loosely-Coupled Architecture' [16] for an integrated navigation system [16], as it can be seen in the figure 3.2.

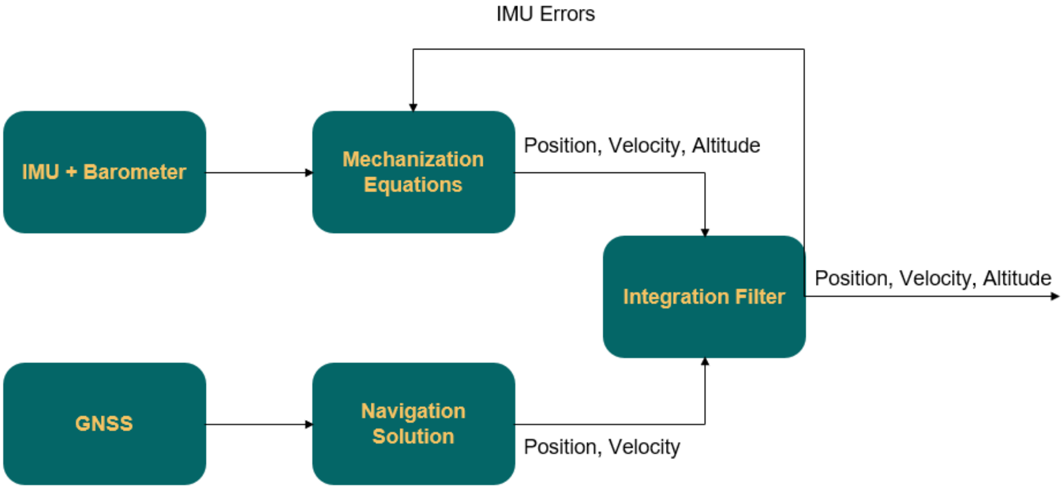


Figure 3.2: Combined navigation system

3.1.2 Detect and Avoid System

To ensure safe operation, sensors are needed to recognise any change occurring in the surroundings, to evaluate the information and to make decisions adequate to resolve hitches or to pinpoint the landing platform for precision landing.

Reasons for Infrared Time of Flight Sensor. Among all the available options for the detection purpose usable in a A/C, IR sensors were chosen for City-Del as they offer visibility at night [2]. That enables the ability to offer ceaseless delivery service with a wide range of feasibleness across different weather conditions.

To clinch increased sensibility, the drone has four sensors with 60 m range [40], positioned on the front, rear and on both the sides. Moreover, there is another distance sensor at the bottom side with the range of 14 m, having higher processing speed of 1000 Hz and accuracy of 4 cm [41] to escalate safety. The extended range of 60 m from the sensors is of much significance as it provides a time window of nearly 2 s to the A/C to evaluate the variation in the surroundings, when it is moving even at its highest horizontal speed of almost 35 m/s, at the same time promising an accuracy of 1.5 % [40] even for sensing an entity at the limit of its range. To confirm accuracy while landing, one IR camera sensor is installed facing down side from the A/C to locate the landing platform where an array of IR rays is used for identification (see section 2.1.3) [31].

The integration of IR sensors with the time of flight (TOF) sensors makes the detection principle easier with increased accuracy and decreased price [6]. The sensor sends IR rays and then measures the time the reflected IR rays take to come back from the obstacle in the path, which is displayed in figure 3.3.

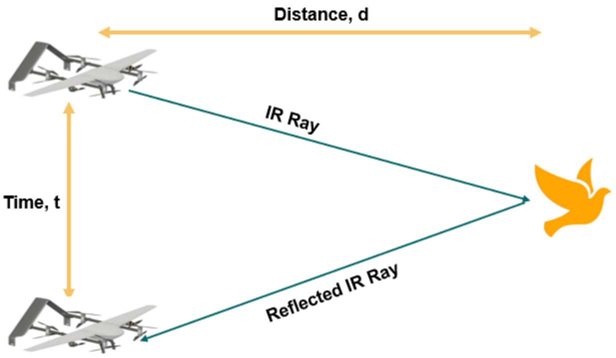


Figure 3.3: IR TOF sensor principle

From this time difference of the rays being sent and receiving the reflected rays, the distance is measured between the A/C to the obstacle, using the following equation [28]:

$$d = \frac{c \cdot t}{2} \tag{3.1}$$

Where d = distance, c = speed of light and t = time between the ray sent and reflected ray received.

While there is a possibility of IR-TOF sensors getting effected by reflections or by other infrared ray sources, the superiority associated with the components *TeraRanger one* and *TeraRanger Evo* 60 m as collision avoidance sensors and *IR Lock Sensor* as landing sensor prevails over the issues, having the advantages as followed [40] [41] [31]:

- Wide range of visibility across different conditions, even in dark environments
- Direct process to extract the distance information out of reflected signals
- Higher range of detection
- Higher speed of processing information
- Increased accuracy with reduced size and weight
- Simple and compact system with easy implementation
- No adverse effects on vision

3.2 Communication

For proper functioning and map-reading, safe flying and avoiding collision, a continuous connection link is required in the City-Del drone for the entire range of operation, having a high speed for data transferring and minimal latency, to communicate from air to ground and vice versa, as it can be seen in figure 3.4.

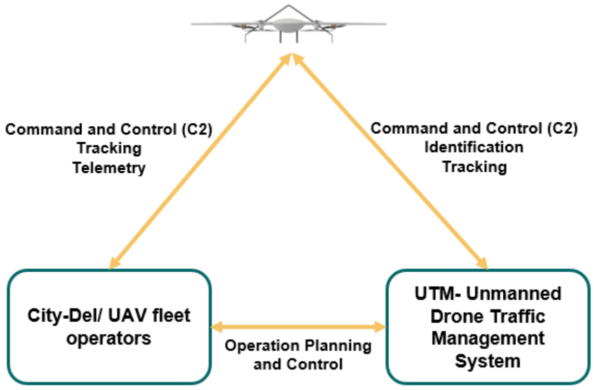


Figure 3.4: Communication process between A/C and ground

To decide on the communication technique in accordance with the requirements for the delivery service, all the available options were considered and compared, to settle on the suitable alternative, which is displayed in the following table 3.1 [50].

Table 3.1: Communication techniques for UAV

Specification	Direct Link	Satellite	Ad-Hoc	Cellular
Coverage	+	++	+	++
Data Rate	-	++	+	++
Latency	++	+	-	++
Cost	++	-	-	++
Weight	++	-	++	++

The main requirement with the delivery A/C is to have a continuous connection between the unmanned drone traffic management system (UTM) and the system on board as well as with the fleet operators, which would have been possible with either satellite connection or utilising the existing cellular networks (NW). But while having a continuous connection it is also important to have a lower delay in the data exchange process, which in comparison to the cellular NW is quiet high in satellite communication [50], so it is decided to use cellular communication for the purpose, utilising *Botlink XRD* [5] modem along with a Subscriber Identity Module (SIM) card on board to confirm the beyond visual line of sight (BVLOS) delivery of goods.

The existing structure of cellular network reduces the cost of communication set up, while the SIM card used for communication also bestows unique identity for the A/C, making it viable for the UTM to distinguish between the A/Cs and their fleet operators for consistent and seamless operation [39].

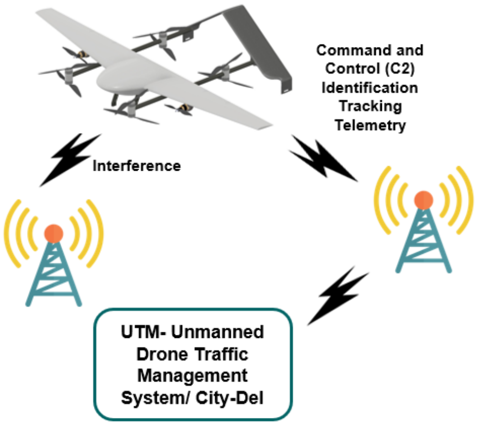


Figure 3.5: A/C communication via cellular NW

Even though utilising the cellular network for A/C's communication comes with the issue of interference, increasing with the A/C's escalation as shown in figure 3.5, but by maintaining the fly height at 120 m the aim is to keep the interference effect to minimal, while utilising the positive aspects of the technique [49], as:

- Coverage over a wide area with high speed connection
- Reliable and secure connection for uplink and downlink data exchange
- Distinct identification of individual A/Cs and their operators
- Tracking of A/Cs using coverage network tower
- Lower latency over the connection (50 ms over 4G, possibility of having even lower delay with 5G)
- Lower cost of operation and lower weight of system on board

4 Noise

Due to increasing noise emissions in cities, the following chapter gives an overview of the noise emissions of the concept. The first subsection detects and discusses the critical sources of noise. Afterwards, possible solutions for noise reduction are presented and evaluated to ensure a reasonable sound level. This leads to a selection of several noise reduction approaches, which are implemented in the concept [37] [42].

4.1 Sources of Noise

The relevant sources of noise within this concept are the electric engines in combination with rotors. The combination of these parts is the reason for the majority of the noise. The source of noise can be split into several components. The major component is called rotational noise, which is a combination of interaction between air, rotor blade, and air mass repression through rotation of the blade. Through a periodic influence of blade forces upon the air, a sheer periodic acoustic pressure is generated. In addition to this stationary load, a variable load on the rotors acts due to the aerodynamic profile. It indicates a harmonic blade load, which is responsible for the high-frequency part of the rotational noise. This high-frequency part is noticed as the *buzz* of the UAV. The buzz increases with the rotation speed of the engine rotor combination [32].

4.2 Noise Reduction

In order to reduce the rotational noise, a minimization of the surface load is necessary. A possibility of lowering the surface load and the amplitude of the harmonics is to increase the number of rotor blades. However, the fundamental frequency increases. To reduce the noise, the standard number of rotor blades can be increased from two blades to three blades. As a result, the fundamental frequency increases, which leads to more significant noise emissions.

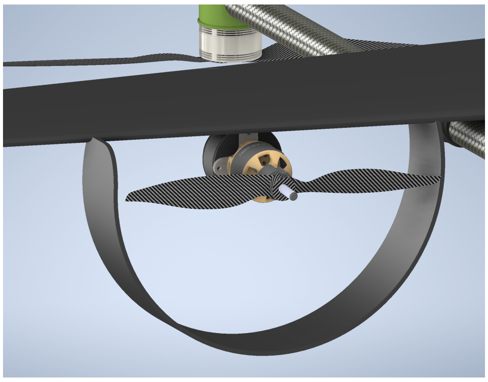


Figure 4.1: Horizontal rotor with cover

For a noise reduction, the rotor diameter must be increased to enable reduced emissions but keeping the performance at the same level. Rotors with three blades enable a reduction of noise. Another method of reducing the noise is to coat the rotors, which leads to a directed and concentrated acoustic noise. For this purpose, a cover made out of carbon fiber reinforced polymer (CFRP) is used, which guides the acoustic noise in the flight direction [11].

Autonomously, these two methods have major disadvantages for the overall concept. In the case of the three-blade rotors, there is an increase in weight, which necessitates a greater drive power. A coat around the horizontal rotors would lead to an increase in weight and to a break in the pressure load on the bottom surface of the wings, which would lead to a greater impairment within the flight behavior. Therefore, the noise was reduced by the following concept-friendly measures:
First, vertical rotors were chosen. The vertical rotors are two-blade rotors with a diameter of 19 inches. Due to the increased oscillation with the diameter and the resulting vibration, which leads to an increase in noise, they are limited to this size. In addition to limit the rotor diameter a vibration absorber is installed under the rotors, which is intended to reduce the vibrations that occur. The lower rotor diameter

would lead to an increase in the fundamental frequencies compared to a larger one. This is solved with the coaxial arrangement of8 rotors at four points. The coaxial arrangement enables small rotors to run at lower rotation speeds with the same output. This is beneficial since the human ear only perceives minor rotation speed or frequency at a very high volume. Furthermore, decibel measurements next to similar engine rotor combinations have shown a volume range between 85 db and 87 db, which are not harmful to the human ear [22] [42] [32].

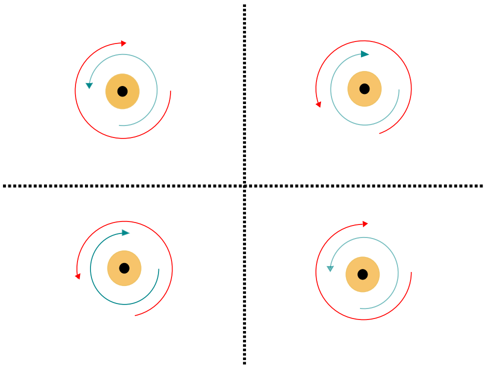


Figure 4.2: Directions of the rotation

5 Safety and Reliability

During the mission the UAV operates in the city, where it is first and foremost important to provide the safety of the population. Furthermore, the integrity of the package, that needs to be delivered, must be ensured. For this purpose, the measures within the concept are made visible.

5.1 One Engine Inoperative

Several errors or failures can be caused during the mission of a A/C. These errors include technical failures that can result from wear and tear.

Vertical Engine Failure. In the event of a vertical engine failure, the coaxial arrangement ensures the stabilization of the descent and climb. Switching off the diagonally lying motor assures that the equilibrium is maintained. This prevents an uncontrolled flight and a safe landing of the A/C is still guaranteed.

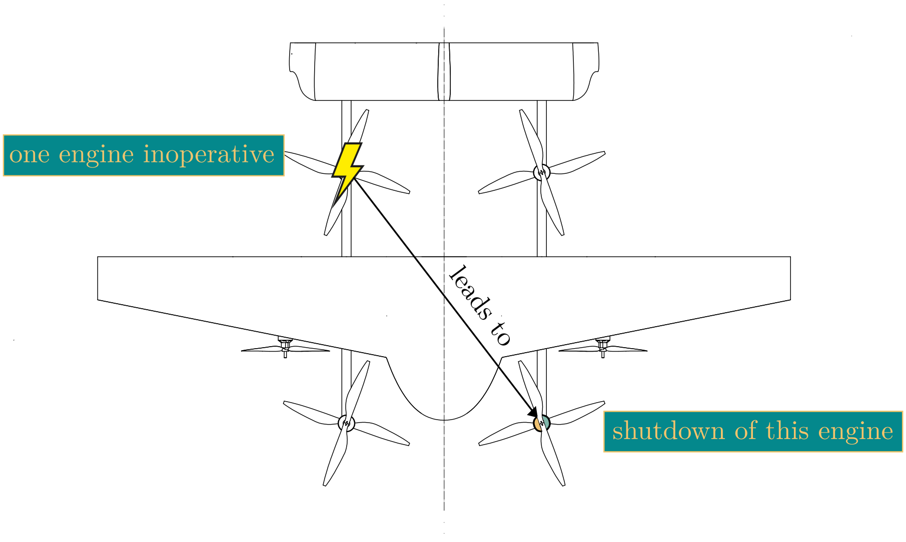


Figure 5.1: Engine failure

Table 5.1 shows the thrust-weight-ratio per motor during variable flight levels at different phases. To ensure a safe landing the thrust-to-weight ratio (TWR) must have a value of at least 1. Using calculations, it can be determined that a safe landing of the drone is guaranteed by the necessary thrust. Complications can occur in the event of extreme failures, such as a loss of four engines. During the mission, on flights in the lowlands a maximum loss of two engines can occur without a necessary increase in rotation speed, due to the thrust of one motor. On the return flight up to four motors could be turned off. When the A/C flies in high areas during the mission phase, the remaining engines must be driven to overload, if two engines fail. This is possible thanks to the controller. During the return flight where the package has already been delivered, the loss of two engines can be compensated because of the weight loss. This means that even with up to two engine failures, the drone is partially maneuverable and always capable of an undamaged emergency landing. Hence, a harm of the population can be eliminated.

Table 5.1: Thrust-to-weight ratio during failures

Flight level	**Phase**	**TWR**	**TWR per motor**
0 m	Mission	1.60	0.200
	Return	2.00	0.250
2500 m	Mission	1.00	0.125
	Return	1.40	0.175

Horizontal Engine Failure. In an unlikely event of a horizontal engine failure, both engines are turned off and the A/C switches from horizontal flight mode to vertical flight mode in order to maintain a stable flight position. The configuration of the rotors leads to an A/C maneuvering like a multicopter. In this mode, a safe landing environment is selected. Depending on the time of failure during the mission the aircraft is able to fly up to 10 km. For a worst case scenario when only the backup of 10 % battery capacity is left, the maximum range is still 1 km.

5.2 Unexpected Power Loss

In the event of an unexpected loss of power, an emergency buffer battery (*BUFFER-Pack* $3 \cdot 40$ *V*4.8) is installed in the A/C. It provides and stabilizes the necessary electricity, which operates the flaps and the sensors required for a safe landing up to 45 s. The maneuverability is guaranteed with this solution. As already stated in section 2.3, a descent rate of this magnitude is possible without the destruction of the A/C. Furthermore, this emergency battery together with the help of a capacitor, acts as a bypass during the replacement of the main battery within the home base to prevent the avionics from shutting down and restarting. In addition to that, the bypassing eliminates errors that can arise when realigning the sensors.

5.3 Disoriented GNSS Signal

For navigation, the A/C makes use of a combined structure of IMU, GNSS and Barometer, hence rather than depending on only one sensor to gain the data about navigation, the decision is based on multi sensor input to steer the A/C explicitly to the destination and achieve desired elevation. The combined structure of having inputs from numerous sensors is of much significance as it helps to diminish the effect of jamming or spoofing, if condition emerges, or any other disordering of the GNSS data, whether sensed by the A/C itself or communicated by the UTM. To decide on the pathway to follow, the data from IMU and barometer are integrated with the data from GNSS. If any dissimilarity is sensed in the datasets from both the sources, the aircraft detects an issue and shifts the navigation system from combined formation to IMU and barometer only, removing GNSS sensor dependency. Depending on its current position, it chooses to move towards the nearby landing platform or the home base to ensure hazard-free functioning.

6 Business Case

An unconventional technology proposition is inadequate without an inventive business intention. After a detailed explanation of the technology, this chapter elaborates more on UAV's business prominence for delivery service in urban areas.

6.1 Problem

Courier, express and parcel (CEP) service providers are currently facing a hurdle in delivering goods in urban areas, mainly on the last mile segment. The upsurge in e-commerce during the recent years and demand for express or same day delivery by consumers in urban areas has made the process more challenging. Furthermore, due to the high number of CEP service providers in urban areas, it is essential to cater to customers with lower costs to survive in the competitive market [13].

A study aimed at investigating customer behavior on CEP service reflects that around 47 % choose to collect parcel elsewhere than home and 73 % consider free delivery as an important factor while purchasing goods[48]. The cost spent on last mile segment forms a significant portion of the total cost spent on delivery service [33]. In the past few years, due to the expanding number of residential freight trips observed in urban areas, CEP service providers have been looking into a new transportation management strategy aimed at residential freight trips [45]. One such measure like collection-and-delivery point, has been playing a major role in urban last mile delivery.

6.2 Solution

The City-Del drone provides around the clock solution for urban last mile delivery for small packages through A/C equipped with precision landing, capable of delivering goods within a radius of 15 km within a short time of 20 minutes at a lower cost when compared to available alternate solutions in the market. City-Del plans to operate in a Business-to-Business market and integrate into an existing value chain of established CEP service providers like DHL, UPS and FedEx. This strategy would also help in gaining valuable market insights through collaboration and an opportunity for high scalability in a short period.

The City-Del drone can be used to transfer goods like medicine and electronics from logistic hub to landing platforms at the customer or to already existing collection points situated around the city, which can be further adopted to automated collection centers and even delivery vehicles. The end consumer has the opportunity to collect his delivery in under 30 min after the order without needing his own landing platform. The proposed solution can also be used by companies for Just-in-Time delivery within urban areas for goods weighing less than 2.5 kg.

6.3 Vision

City-Del aims to operate in a Business-to-Business market and cater to the challenges faced by CEP service providers in last mile urban delivery through the sale of A/C at lower acquisition and operational costs. This eliminates the usage ground delivery system and promotes safety in congested urban areas.

6.4 Strategy and Value Proposition

Strategy of City-Del is to target a niche market of CEP service providers operating in Europe. Major part of the revenue would be as a portion of sale of products and minor portion from sale of spares and additional services through the operating period. Also provide solutions specifically for last mile segment in urban areas and offer the following value proposition to the customers

- Faster delivery time within 20 minutes.
- Lower operation cost compared to alternate solutions.
- Low setup costs.
- Zero emission of poisonous gases to environment.
- Safer compared to other conventional delivery during loading and unloading in urban areas.

6.5 Market Segment

The emerging UAV technology is used for various applications and is gaining a lot of attention from investors and academic research. The global UAV market is expected to reach a value of $43 billion for the year 2024 and portion of this market constitutes usage for delivery purpose[35]. A study projects a demand for 70, 000 UAV to deliver a 200 million packages annually in Europe at 2035 [43] out of which 11, 000 drones are estimated to be used for delivery purpose in UK by 2030 [23]. At present 3, 500 million CEP are delivered annually in Germany alone [15]. The usage of UAV for delivery is considered as Total Addressable Market (TAM) for City-Del. UAV delivery is considered to be a disruptive technology and would follow the stage of exploitation from the year 2027 to 2037 [43].

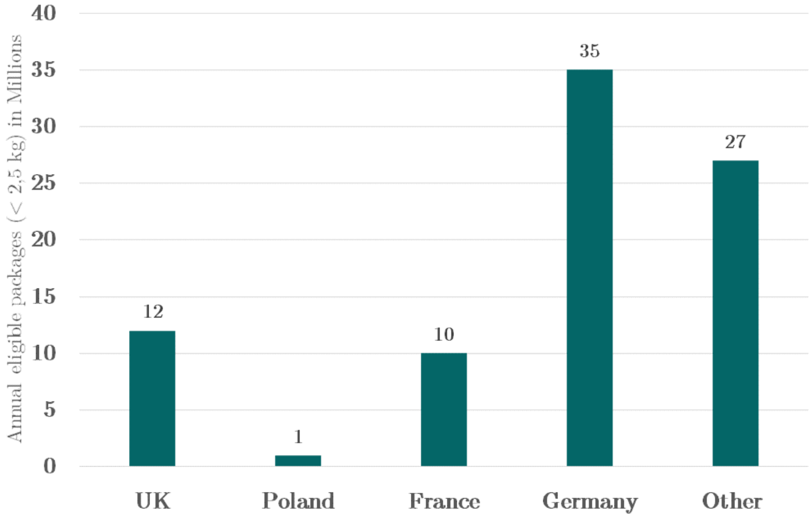


Figure 6.1: Packages eligible for UAV delivery

City-Del is focused on providing Business-to-Business solution to CEP service providers in urban areas for the European market as served addressable market (SAM). The European market accounts for 20 % of the commercial UAV market after North America [3]. Even with the existence of advanced technology, absence of consumer acceptability and unfavourable regulations for operation in urban areas are the challenges currently faced by UAV sector. However City-Del plans to enter the market in 2025 during the exploitation stage of UAV for delivery purpose with favourable and harmonized regulation for operation of UAV in urban areas around member states of Europe. The aim is to capture around 5 % of the European market (SAM) with an annual revenue of 21 million euro by producing 3500 units of A/C at 2035 as serviceable obtainable market (SOM).

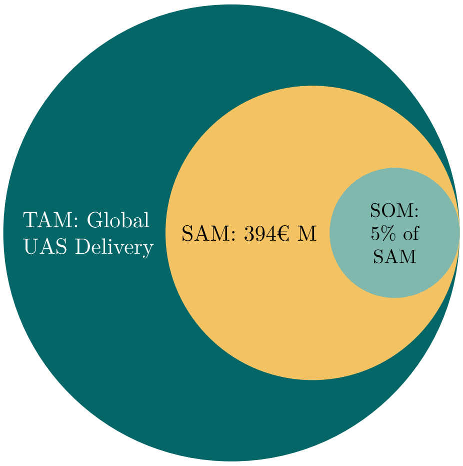


Figure 6.2: Market size evaluation for City-Del

6.6 Competitive Landscape

City-Del identified 4 major competitors, providing A/C delivery solutions but City-Del addresses problem related to a niche customer segment of CEP service providers in urban areas. Most competitors are mainly operating in US market or on rural areas with limited infrastructure as shown in the below table 6.1.

Table 6.1: Current market of UAV for delivery [46][14][51][17]

Competitor	Customer segment	Operating area
Wing	Food and Pharmaceuticals	US, Australia and Finland
Uber Eats	Food	US
Zipline	Pharmaceuticals	US and South Africa
Flytrex	Food	US and Iceland
Ehang	Logistics	China

There exists a gap in solution of UAV for urban areas specifically designed for CEP service provider with a value chain business model in Europe. Whereas most of the available solution concentrates on delivering goods to the end customer, City-Del strategy is to deliver goods from hub to collection centers in urban areas.

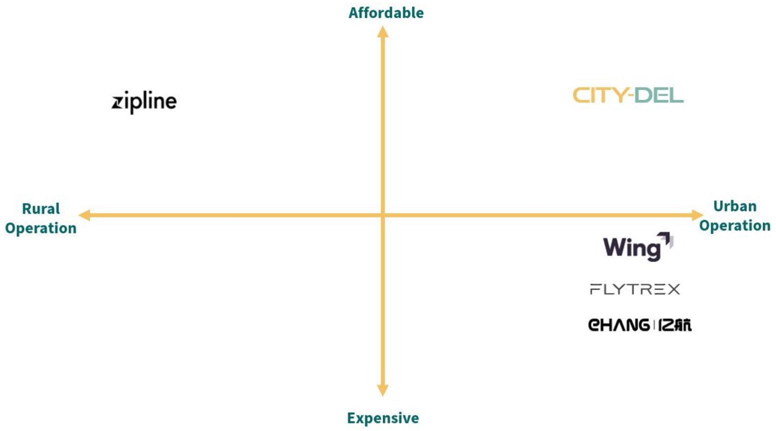


Figure 6.3: Competitive landscape for UAV delivery

6.7 Pricing Strategy

As mentioned before, sale of product constitutes to prime portion of City-Del's revenue. Lower acquisition cost plays an important part in the sale of products and competitive pricing is attractive. But however, this cost is not overshadowing the unique features offered by City-Del.

6.7.1 Acquisition Cost

As the name suggests, these are the cost incurred in order to acquire and place A/C in working condition. This cost includes the cost of the A/C with the landing platform and system for retrieval and loading of packages into the package carrier. The cost of A/C is calculated as bottom up and activity-based approach [44]. In this approach costs are calculated from individual parts and related process into subsystems, combination of such subsystems into system and group of system form the complete A/C. The City-Del A/C is divided into 6 different systems as shown in figure 6.4. The advantage of bottom up activity-based approach are proved to be accurate and take into consideration the costs of every part provided by the responsible person for each sub system [44].

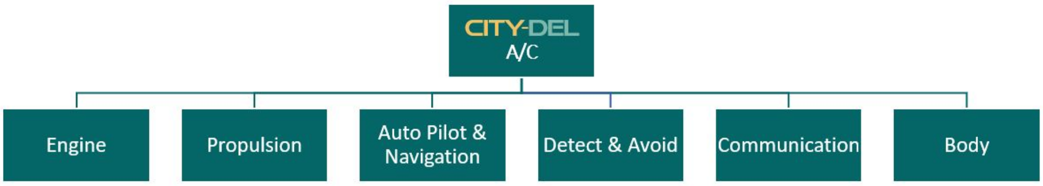


Figure 6.4: Classification of different systems [44]

The unit price of A/C is 5,860 € with 20 % profit. The cost split of individual system on unit A/C is represented in figure 6.5.

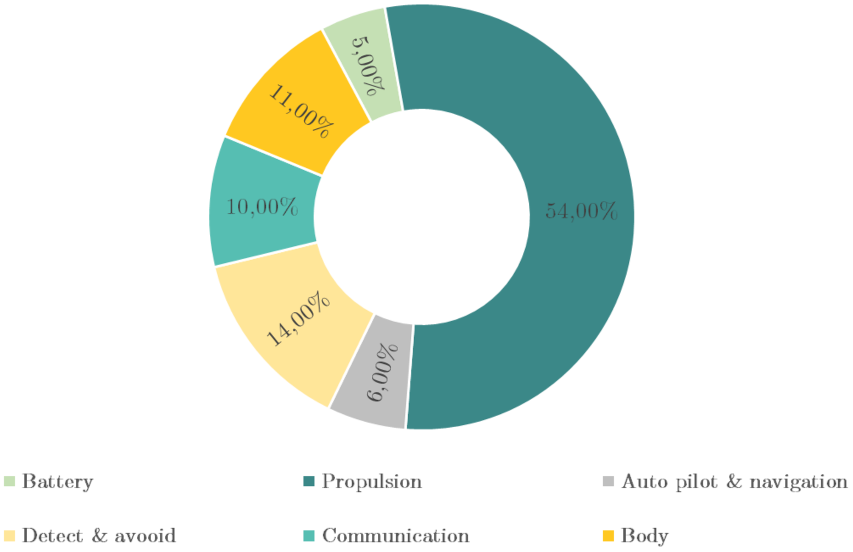


Figure 6.5: Cost split of unit A/C

The A/C landing or takeoff platform can be installed easily within a space of 2.50 m × 2.50 m. The IR ray equipped landing platform would cost €200 per unit and can be further modified depending upon the individual requirement of each CEP service providers to operate from logistic hub to collection centers around urban areas. The flexibility of portable landing platform is considered to be a unique offering that City-Del offers to its customers.

6.7.2 Operation Cost

The operational costs of A/C are distinguished as fixed costs and variable costs. Fixed costs are incurred even when the A/C is not in operation and constitutes expenses from annual maintenance, spacing cost, insurance and depreciation. On the other hand, variable costs depend on the usage of A/C. The operation costs are calculated according to the Gudmundsson model [21] but few parameters are adjusted to suit the operation model of City-Del A/C.

- **Electricity Cost**: This cost refers to the cost spent to power the A/C. A fully charged City-Del A/C is capable of travelling with a cost of 0.2 €.
- **Maintenance Cost**: Maintenance cost can be further distinguished into predictable maintenance such as replacing of batteries and propellers and unpredictable maintenance. The batteries are rated with 150 discharge and charge cycles for a superior efficiency. It is also important to consider the unpredictable maintenance during the operation period.

- **Labor cost**: This involves the manual labor in overseeing the operation of A/C and support in charging the batteries. It is assumed that one operator can oversee operation of 10 A/C at a time.
- **Spacing cost**: Cost spent on storage of landing platform and A/C.
- **Insurance Cost**: Includes insurance for the A/C, the goods carried by the drone and also damage to property in case of any accidents. The insurance amount for commercial A/C is dependent on the type of A/C, location of service and industry [30].
- **Cost of Capital**: This amount constitutes to the repayment of the capital spent on the A/C. It is assumed that the loan would be re payed in 5 years at 5 % rate of interest.
- **Network Cost**: City-Del A/C maintains communication with UTM through cellular network, utilizing a sim card and the charges differ depending upon the network provider.
- **Licence Cost**: It is mandatory to have drone driver's licence to operate commercial drone with a takeoff weight of more than 5 kg. A license according to the specification of German Federal Aviation Authority would cost 180 € and the license is valid for a period of 5 years [10].

The hourly operating cost of A/C are calculated considering the above costs and the results are shown below in the figure 6.7.

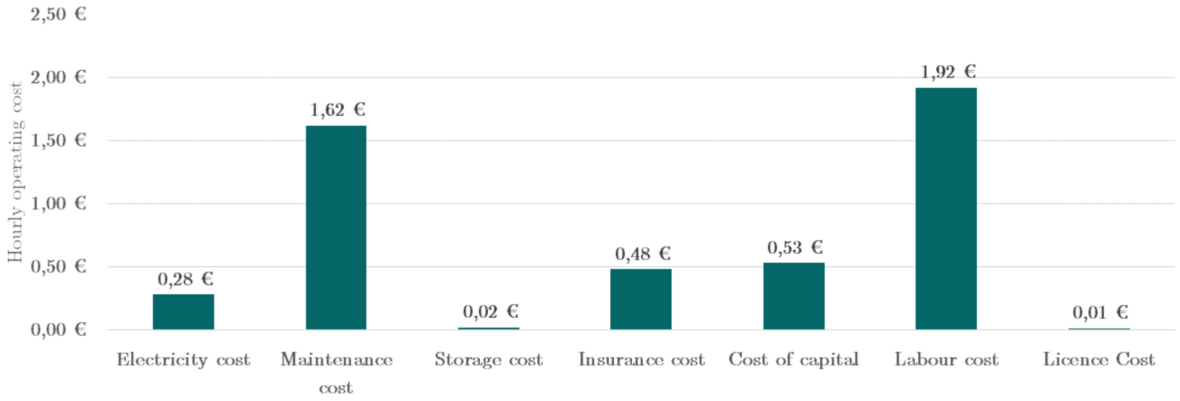


Figure 6.6: Operational cost of City-Del

The operating cost of a unit A/C operating for one hour is 4,86 € and for one delivery 3,3 €. An A/C which operates 10 hour a day and 261 days of a year has an annual operational costs of 12.684 €. The cost split of the annual operating cost is shown in the figure 6.7.

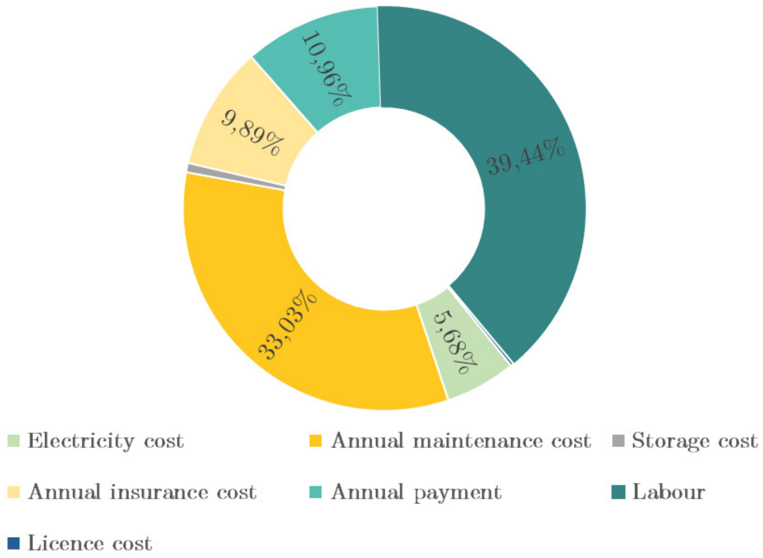


Figure 6.7: Annual operating cost of City-Del

6.8 Regulation

Special regulations are applicable for UAV operating on beyond visual line of sight. Due to increased use of UAV on different sector for commercial use and looking into the future demand and efficiency, government and city management are evaluating the laws and making the necessary changes on the regulation taking safety into consideration. CITY-DEL plans to operate in European market and it is necessary to study and evaluate the local law and regulations for operation of A/C. The SESAR Joint undertaking provides a wider aspect of the regulation in Europe and it is as shown in the table 6.2 below [43]. The maximum height limit is for A/C with CITY-DEL specification for evaluation.

Table 6.2: UAV regulation in europe [43]

Country	Weight limit	BVLOS	Maximum Height
Germany	25 kg	In segregated airspace	100 m
France	150 kg	Test flights	150 m
Italy	EASA Basic Regulation	Allowed	-
Netherland	150 kg	Not allowed	120 m
Poland	150 kg	In segregated airspace	-
Sweden	150 kg	In segregated airspace	-
Switzerland	150 kg	Allowed	No limit
UK	150 kg	Allowed with conditions	400 ft

The European Commission recently published new regulations for UAV considering this to be an open type and not to include all regulation applicable to aircraft on all member states. However this signifies essential requirement related to safety, privacy, protection of personal data and security [12]. The regulation differ from one member state to another based on type of use, mode of operation, weight and other different criteria.

7 Conclusion

The aim of this project was to create a technical design and a business concept for an autonomous package delivery system within urban areas as part of the JOINT NASA/DLR AERONAUTICS DESIGN CHALLENGE 2020. The CITY-DEL drone fulfills those requirements by keeping all the demanded specifications. The design of the autonomous unmanned vehicle is achieved through various configurations and methods. Those methods are summarized in the following statement and further courses of action will be discussed.

The configuration selected and presented in this report is a composition of common and modern approaches for autonomous drones. Because of its hybrid concept consisting of a multicopter and an aircraft the CITY-DEL drone provides optimal flight characteristics during all flight phases with multiple key technologies:

The coaxial alignment of the 8 high efficiency vertical rotors result in a four point configuration and thus ensure high safety and reliability. To achieve strong aerodynamic performance in cruise flight operations the aircraft is mounted with optimized trapezoidal wings enabling a fixed wing concept with a corresponding V-shaped empennage. The chosen V-Tail is characterized by several features, just like working as a lightweighted empennage as well as providing the rear landing gear of the aircraft. The introduced configuration of engines and rotors lead to a reasonable stability and maneuverability during climb and descend. The transition phase excels in a change over from vertical to horizontal flight mode of the drone. When starting the horizontal flight, the vertical engines still produce the necessary thrust to cover the short period of time before stall speed is transcended.

While flying in both modes, vertical and horizontal, multiple sensor structure in conjunction with cellular communication and GNSS system provide eminent safety-related features and simultaneously allow essential communication and navigation in urban areas. The chosen *TeraBee* IR-TOF sensors provide awareness in both near and far zone with their varied range of operation and fast processing speed satisfying all the needs for safe service. With increased accuracy and visibility while having decreased cost, size and weight, these sensors set out to be the perfect course of action to avoid any collision for the CITY-DEL drone. The selection of highly complex sensor systems require a well functioning data processing hard- and software, which is realized with *Pixhawk 4*. This processor enables the ability of a high range of configurations, meaning that the drone can be adjusted or even customized to cover several environmental changes. Even though the CITY-DEL drone is adapted for urban and suburban areas, heights of 2500 m can still be coped. The energy supply for engines and avionics is provided by a battery pack consisting of an arrangement of 10 batteries in parallel and 6 in series. To preserve the battery cells 10 % power backup is kept in every situation and at the same time serves as an additional supply for emergency cases.

The considerate logistics headquarters allow for a short turnaround time due to fast processing on ground by exchanging the package carrier together with the battery as a whole. The navigation, collision avoidance and continuous communication system is structured in accordance with the requirements, for which the energy supply is kept connected continuously.

A possible business case scenario is developed for a B2B company providing last-mile delivery solutions considering the market demand, customer acceptance, competitive landscape and pricing. An investigation on the current regulation of the target market was conducted to realise the plan of market entry in the year 2025 when the regulations are harmonized to capture the window of opportunity in the technology exploitation stage on the usage of UAV for delivery purpose. Further studies in the UAV sector is recommended to develop the CITY-DEL drone in detail to improve parameters like costs, noise emissions and aerodynamics.

The matters named above need to be followed in continuing studies. A greater aerodynamic examination could lead to even higher performances. By reducing the frontal surface of the aircraft and in this process decreasing the drag coefficient, the top speed of the drone would increase respectively. Furthermore, the suggested components for the drone could be adjusted, when going into mass production. Nevertheless, the implemented components presented in detail in the report allow an entry into service as soon as the regulations for drones are adjusted.

Appendix

A Visuals of the aircraft

A1 Presentation of the Drone

A2 Pressure distribution

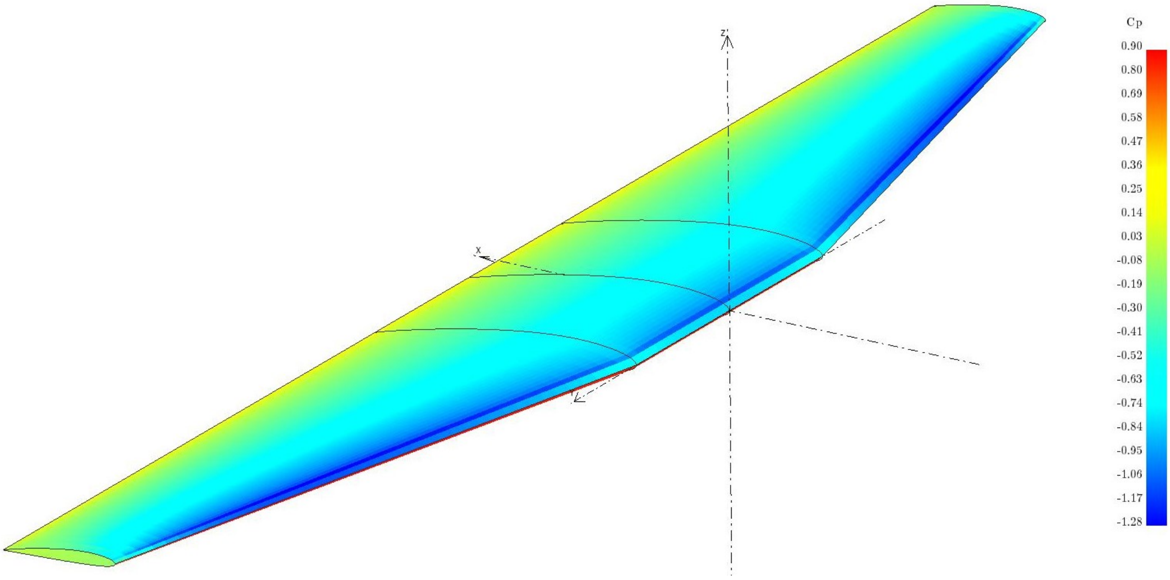


Figure A2.1: Visual pressure distribution over the wing and simplified body

B Technical Design

B1 List of Requirements

Table B1.1: List of requirements

		Parameter			
	Description	**min**	**exact**	**max**	**Unit**
1	Task				
1.1	Delivery via air transport				
1.2	Delivery to designated landing platforms				
1.3	Autonomous unmanned aircraft				
2	Requirements of the A/C				
2.1	Avionic and Autonomy				
2.2	Minimize harm in case of system failure				
2.3	Positioning system				
2.4	Idendification system (UTM by FFA)				
2.5	Communication system				
2.6	DAA system (detect and avoid)				
2.7	Redundant onboard alitude measurements systems				
3	Mission				
3.1	Point to point distance (HQ to landing platform)	15			km
3.2	Operation time (HQ to landing platform)			20	min
3.3	Two deliveries over 15 km w/o human intervention				
3.4	Rainy wheater conditions				
3.5	Operation height	120		150	m
4	Engine				
4.1	Any type of power systems				
4.2	Noise must be acceptable for humans	84		87	db
4.3	Thrust	188			N
4.4	Fly in winds			20	kn
5	Delivery				
5.1	Delivery launch every two min.				
5.2	Size of package		$15 \cdot 15 \cdot 15$		cm
5.3	Weight of package		2.5		kg
5.4	No drop or lowered from a hovering vehicle				
6	Body				
6.1	Waterproof				
7	Requirements of Landing and Takeoff				
7.1	Climb altitude within one mile of takeoff	120			m
7.2	Descend within one mile to the designated landing sight	120			m
8	Requirements of Landing Platform				
8.1	Lenght			15	m
8.2	Wide			7.5	m
8.3	Maximum height			2.500	m

B2 Flight characteristics at 2500 m altitude

Table B2.1: Overview of the mission and return home at max. power (0 °C and 2500 MSL) with adapted vertical rotor size of 21 inches and rotor size of 12 inches

	Property	Mission	Return	Unit
General	Takeoff weight	11.72	9.22	kg
	Battery capacity	52.00	38.00	%
Vertical	Rate of climb	2.00	3.90	m/s
	Flight time	1.70	1.70	min
	Battery usage	12.00	8.00	%
	Thrust-to-weight ratio	1.40	1.70	–
	Max. current	22.21	22.21	A
	Max. voltage	20.65	20.65	V
	Max. rotational speed	5041.00	5041.00	1/min
Horizontal	Stall speed	92.00	82.00	km/h
	Max. speed	146.00	146.00	km/h
	Flight time	14.10	14.10	min
	Battery usage	40.00	30.00	%
	Max. current	42.55	42.55	A
	Max. voltage	21.00	21.00	V
	Max. rotational speed	11 987.00	11 987.00	1/min

B3 Package carrier

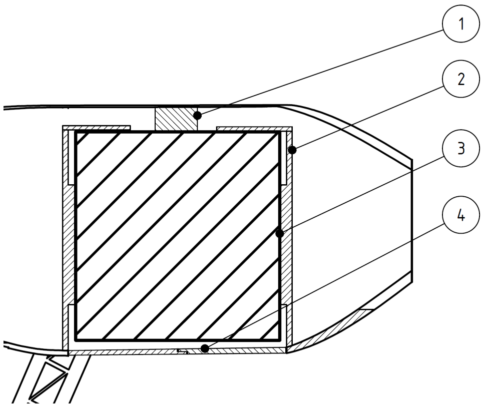


Figure B3.1: Working principle of the package carrier

Table B3.1: Labeling of the package carrier system

	Part
①	Permanent Electromagnet
②	Carrier
③	Package
④	Flaps

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