# Smart Fabrication of Robotic Systems
## *A Project with University Students*

Vanessa Nickel, Pablo Ottersbach, Robert Reichert and Michael Schäfer
*Institute of Computer Science, University of Applied Sciences Ruhr West, Tannenstraße 43, 46240, Bottrop, Germany*

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Abstract This paper describes the progression of new construction technologies to rapid prototype multicopters. Based on ideas of the growing maker-community, university students used 3D-printing and laser-cutting technologies to build copters with individual features. In this case a flight without visual contact should be realised by mounting a camera in front of the copter. Both technologies were used in competition and the better requirements satisfying copter was built.



# 1 INTRODUCTION

Since a few years the RepRap is conquering the market (N. Gershenfeld, 2012). This is a 3D-printer, which is used for Rapid Prototyping and produces components by printing thermoplastic with high accuracy (Possibility of reconstruction of dental plaster cast from 3D digital study models, 2013). Its name RepRap is the shortcut for Replicating Rapid Prototyper. Due to falling investment and running costs (McKinsey & Company, Loc. Cit., 2013) a large amount of people are using this process now.

The advantageous in contrast to different processes are the endless possibilities to create and construct (D. Jijotiya, Dr. P. Lal Verma, 2013). The RepRap is able to print a lot of components, if necessary by using a supporting structure. So it is also able to replicate itself (T. Simonite, 2010).

With these newest technology students built a Copter supplied in their project work. The target is the knowledge about different materials and to choose the best components for the copter.

Another possibility is the construction of the frame with beech plywood using a CNC laser cutter. The frame is designed of beech plywood with positioning of components in a different way compared to the printed model based on different characteristics.

Furthermore the results of printed components were compared with cut-off-pieces. Thereby is shown the interest of the particularities of design and manufacturing problems as well as the advantages and disadvantages of the processes and the constructed frames.

To realize a flight view without viewing the copter, a Go Pro camera is installed at the front of the fuselage. The image is transferred to fat shark glasses which contain a small monitor inside.

# 2 RELATED WORK

## 2.1 Copter

By now there are a lot of different types of copters buyable for home-use: Either you can buy it as an already functionable copter or only the single components to build your own.
Copters are professional-used, too; for example to provide dismounted soldiers with aerial reconnaissance capabilities and support in complex urban environments (Hou, M., Ho, G., Arrabito, G. R., Young, S., Yin, S., 2013).

There are many differences between preinstalled copters: From basic models, which are only be capable to fly, over non professional FPV drones, like the parrot AR Drone, to high professional Copters used by industry. Meanwhile they are able to be controlled with smartphones, so a separate radio-remote-control isn't needed (Årzén, K. E., 2013, Zimmermann, A., 2012).

To create your own copter there are many

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choices: In the trade there are complete construction kits availabe which only need to be put together; moreover exist a lot of construction manuals to fabricate your own copter by yourself.

The disadvantages of construction-kits are manifold:

- The arms are often airtight, so the air resistance is much higher; this reduces the flight-time
- Upgrade the copters with subsequently-installed-cameras is not easy; there could arise problems
- If they have a crash and no predetermined-breaking-points or a very robust chassis perhaps it will break. The consequence would be an expensive repair
- The radio-range is low, maximal like the visual range of the copter
- They haven't a negative pitch or the funk-control doesn't let switch itself

Conclusion: Bad or too cheap components induces unsafely flights and a low flight-stability.

The biggest Problem with all this flying machines is the power of the battery; because of this the TU München already has developed a method to reach endless flight-time with a Laser and a solar-plate fixed at the Ground of the Copter (Technical University of Munich, 2010). If the Laser irradiates the plate, the Drone gets more energy. The disadvantage is that all the time a laser has to shine on it.

## 2.2 RepRap

To build a copter with a 3D-printer, there are five different types of 3D-printer-techniques:

- **Stereo-lithography** (SLA) is the oldest method of 3D-printing: The liquid material is contained in a box where a laser hits on the molecules which is why they connect to each other. A support structure is necessary which easy can be removed after.
- **Selective laser sintering** (SLS) use powdery material which can be plastic, metal or ceramic. The layers apply with a roll-mechanism and will be fuse by a laser. A support structure isn't necessary, only when printing a component without a continuous connection it is needed. An after-treatment is absolutely necessary because it isn't possible to prevent that the powder particles near the printed components sinter, too. Depending on the complexity and the material of the component it isn't easy to remove the support-structure a sand or glass bead blasting is needed.
- **Fused Deposition Modelling** (FDM) uses a thick plastic string which will be heated up by an extruder and cools down on a plate, while creating the final form. A support-structure as well as an after-treatment to remove it is necessary.
- **Laminated Object Manufacturing** (LOM) uses paper or plastic foils which will be glued layer by layer. After every layer it has to rework the contours with a cutting tool. The after-treatment is only to remove the cut pieces.
- **Three-dimensional-Printing** (3DP) works like the SLS-technique with powdery material, but uses a print head and a binder to connect the powder. An after-treatment isn't necessary.

## 2.3 CNC-Laser-Cutter

To build a copter with a CNC-laser-cutter there are many possibilities. The following are the most common:

- **Gas laser** are classified in chemical laser, excimer laser and metal-vapor laser. All are powered by a chemical reaction
- **Dye laser** use an organic dye as laser medium
- **Solid-state laser** which use a solid gain medium
- **Semiconductor laser** belongs to the group of solid-state lasers

# 3 MACHINES AND MATERIALS

## 3.1 RepRap Printer

For this project we used the FDM-printers BFB-3000 and 3D Touch. Both use the thermoplastic-materials PLA and ABS. In earlier times of using the printers PLA had turned out as the better material for large parts: It has sufficient capacity, and a relatively low thermal distortion. ABS has sufficient capacity, too, but the thermal distortion is higher, so the printed layers remove from each other during the printing process and the components becomes unusable immediately.

Useable components are only producible by printing when prevailing optimal conditions. If the temperature and humidity aren't optimal during printing-process the produced components are mostly bad and unusable. Unfortunately the print-box isn't closed so it is difficult to keep the conditions.

## 3.2 CNC Laser Cutter

For this project we used the $CO2_2$-Laser ZING 6030. The advantage of CNC-Laser-Cutter-machines are that it doesn't dependent of specific temperature

range or else. It is possible to cut acrylic glass and wood with a maximal dimension from 300mm up to 600mm. The machine works very accurately and fast with two axes.

### 3.3 PLA

Polylactic acid is a cheap, plant based polymer, which is produced from lactic acid. It is an elastic material and stiff as hard as glass at the same time.
In the printing process the PLA is heated thru the second layer which guarantees a low shrinkage.
Molecular formula: $C_3H_4O_2$
Melting point: 150-160°C
Density: 1210-1430 kg/m³
(Mohd Bijarimi, Sahrim Ahmad, Rozaidi Rasid, 2012).

### 3.4 ABS

Acrylonitrile Butadiene Styrene is a material which deforms much when heated. Because of this it is used only for support-structure when printing large objects.
Molecular formula: $C_8H_8 \cdot C_4H_6 \cdot C_3H_3N$
Print Temperature 230°C - 240°C
Density: 1,04 - 1,12 g · $cm^{-3}$
(Eurapipe „ABS Material“, 2013).

### 3.5 Beech Plywood

The beech plywood which is used is made of five layers and has a thickness of five mm. Because of the layer-structure the plywood is sensitive to bending and buckling cross to longitudinal axis. To stabilise the frame it is necessary to construct the component with another element displaced of 90°, hereafter named ‘T-form’ (fig. 1).

Although beech plywood is quite elastic it is very brittle and breaks down quickly in plastic deformation.

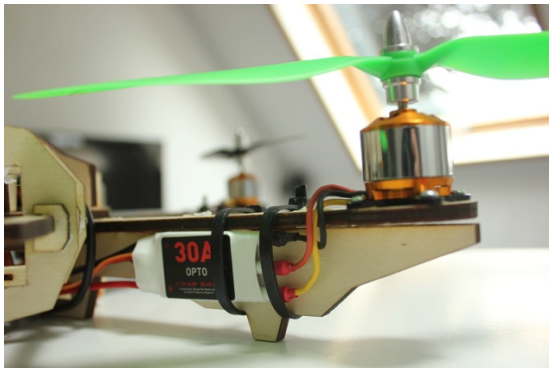


Figure 1: Plywood-copterarm in 'T-form'

## 4 COPTER

### 4.1 Construction of the Frame

The most important thing when constructing a frame is to keep in mind how the components must be placed in. They have to balance the center of gravity in the middle for ensuring a smooth and stable flight. Small deviations from the ideal center can be compensated by the Naza controller (4.4.1).

The center of gravity can be ignored by the construction of the arms, because they are fixed symmetrically, so they balance each other out. This Copter was developed for FPV-flight from the beginning, therefore it make sense to use the camera and the battery as a counterweight for each other.

Moreover the camera has to be fixed enough in the front in a way it won’t film the arms of the copter with its large camera-angel (fig. 2).

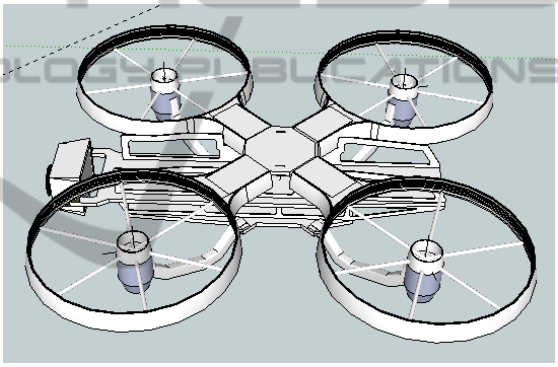

Figure 2: CAD model of the printable copter-frame.

The back of the frame has a specially constructed box which is adapted to the batteries. The fuselage and the side parts are constructed to carry the electric components and connect the protection for the rotors to each other. The plates are perforated to lower the air resistance. The rotor-protections with the cable guide are printed by the RepRap to realize a good stability with a light weight. It is constructed with a special curve to offer a landing surface. In between the bottom there are small grooves to lay the cables inside for not destroying them by landing (fig. 3).

The protection for the rotor is guaranteed by a ring which is fixed at the top and on the bottom with the fuselage (fig. 3, fig. 4).

All the components were fixed with superglue and when necessary with cable ties. It is a very lightweight and quick fixing-method.

The motor should be mounted in the middle of the ring so the rotor is turning inside the protection.

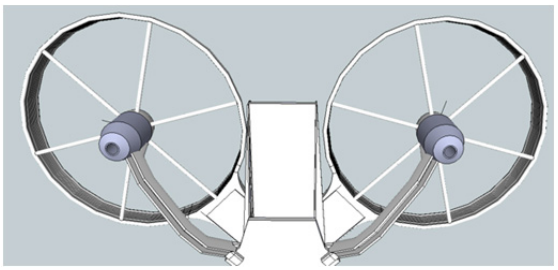

Figure 3: Grooves for cables and rotor-protection.

Figure 4: Printed rotor-protection.

The motor should be mounted in the middle of the ring so the rotor is turning inside the protection. In case of a collision the copter will be shaken, but the rotors aren't blocked and the copter won't fall. Furthermore the ring takes horizontal forces over the spokes, which don't increase the air resistance because of the small size.

The lower parts of the arms support the motor in vertical direction and provide space to put the cables in. Also it serves as landing gear.

Other than the printed frame, where the development-focus was the arms of the copter, for the plywood frame it isn't possible to manufacture a structure as fine as the printed structure. If the rotor-protection were made by plywood, the spokes can't take the forces and will break. Because of that it a simply arm without protection was developed (fig. 5). The focus has been on the fuselage.

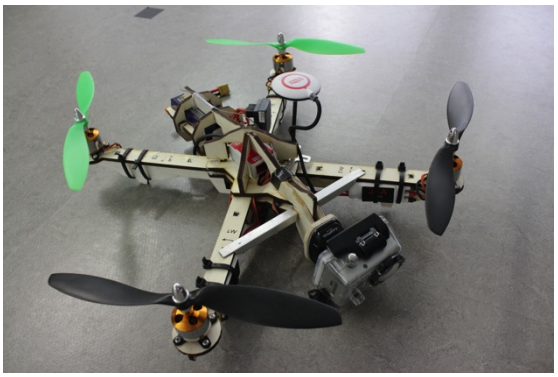

Figure 5: The whole copter made by beech plywood.

As already mentioned in 3.5 there is something to mind when constructing with plywood. That's why there was constructed a plate to put the other components onto this one first. This way the frame was getting a ribbed structure and the plug connection got a better stability (fig. 6).

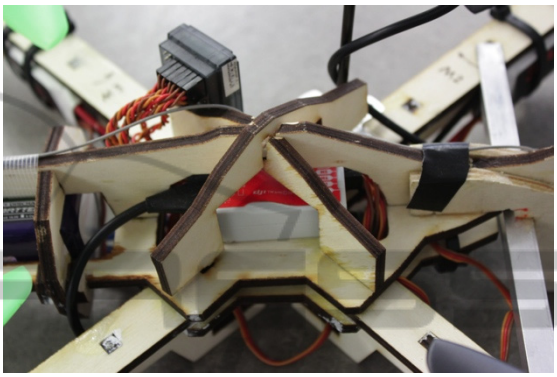

Figure 6: Ribbed structure.

## 4.2 GoPro

The very high resolution of the Go Pro Hero 2 provides optimal video quality over radio communication to the Fat Shark glasses.

Furthermore it is possible to save the videos on a SD Card at the same time.

The Go Pro is fixed with the supplied camera holder on a piece of the beech plywood. (http://www.gopro.com)

## 4.3 Fat Shark

The Fat Shark realizes a clear picture from the Camera to the lenses without solar irradiation in a compact way. Where other lenses with wide-angel-function fail, the Fat Shark delivers perfect results. Moreover it is the only one which is upgradeable with different radio modules and head trackers. (http://www.fatshark.com)

## 4.4 Dji

Dji offers reliable products at an affordable price that are also compatible with many other components. The installation is very simple and the safety concept very well.
(http://www.dji-innovations.com)

#### 4.4.1 Naza

The Naza Main Controller combines many features. It is equipped with GPS, air-pressure-sensor as well as coming-home-function and home lock. It has also the possibilities to compensate the camera mount. (http://www.dji-innovations.com)

## 5 RESULTS

At the beginning the results of the printing-objects were often gone badly and the material broke. The nozzles of the extruders were clogged and had been repaired.

The component size is limited and also the size of the large, straight printable components in one piece. This is because the materials deform if it*s too large and the result isn't usable.

The printing-objects are resistant to shocks and impacts and can also survive falls from height. The way to connect the components between each other by using superglue proved to be efficient.

Because of the problems with the printed components, the frame for the finished copter was fabricated of beech plywood by the CNC-laser-cutter. The cut out pieces are simple to join together and after bonding each other there is enough stability to fly with.

## 6 DISCUSSION

At the beginning the plan was to build the whole copter with printed components. The first components were printed in a good quality, but there were problems to repeat the printing with this high quality:

The material breaks because of the incorrect room-temperature and humidity. By trying we found out that the indoor temperature must be 23°C and needs a humidity of 32-48%. Then the material has an unlimited durability. Unfortunately we couldn't keep the conditions all the time. Some components printed over 24 hours and because of variations in temperature mainly at night the results were unusable.

The clogging in the nozzles can be solved by setting the right temperature in the extruder according the material parameters.

The deforming of the materials happens because the temperature difference between nozzles and printing plate is too high. The material cools down too fast and the printing cannot continue straight. This can be resolved by using a heatable-printing-plate or new software with fine-tuning-modus.

When it is possible to keep the certain conditions there is a good way to print the whole frame in high quality.

As a valid alternative to the RepRap-printer the CNC-Laser-Cutter has been suggested. For the reason that this machine is independent of external influences it is easy to produce the same components again and again in the same quality.

The high stability in addition to a minimal air resistance is easy to realize with the printer because the forms are freely selectable. For the cut off pieces of the CNC-machine it must be aware that plywood only can absorb forces in longitudinal direction and fail when forces acting in transverse direction. That's the reason why the construction must be in 'T-form' (fig. 1).

This art of construction needs a lot of more space and cannot be realized as slim as the printed model, which means that the air resistance is higher.

A big disadvantage in contrast to the RepRap is that the CNC-machine only can produce in 2D, because there are only exist two axes.

The limited size of printable and cut off components and the connection with superglue is the best way to have a strong connection with also predetermined breaking points. This prevents more damages and with these breaking points possible repairs are easier.

## 7 CONCLUSIONS AND FUTURE WORK

In conclusion this paper presents a Quadrocopter-frame built with laser-cut-pieces of beech plywood and also the research on printing a frame with a RepRap. Both processes were compared and it was confirmed that a CNC-laser-cutter is in our case the better way to create a frame even though it has not the same possibilities like the printer.

It must be remembered that the 3D-printing-systems have just started and are still in early stages. The systems are continually refined and extended so they will be less sensitive to outside influences. For printers used by industry it is possible to keep it away from environmental influences and by time it will prevail for home-use-printers, too.

The printable copter components are a new way to build robust and lightweight robotic systems.

In the future there are various possible

applications: for example they could be used to investigate high-rise buildings for cracks, or even to rescue and recover people in need. Flood victims who are hard to reach can be powered up to their rescue with food.

Furthermore this copter already is used "to monitor environmental data like the current $CO_2$ value and other measures for air quality in real time" (Schäfer, M., Jansen, M., Seabra da Rocha, S. F., 2013).

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