A Rocket Experiment for Measurement Science Education

T Mitterer, L M Faller, H Müller, and H Zangl
Institute of Smart Systems Technologies, Alpen-Adria-Universität Klagenfurt,
Universitätsstrasse 65-67, 9020 Klagenfurt, Austria
E-mail: tobias.mitterer@aau.at

Abstract. Measurement of mechanical quantities such as speed, acceleration, angular velocity and also orientations is of crucial importance in many applications and in particular in robotics. In order to illustrate different direct and indirect approaches (integration and differentiation methods) we use an air rocket experiment for a bachelor level university laboratory course. Besides getting familiar with image based measurement, remote measurement and telemetry, the experiment also provides hands-on experience with Newton’s axioms. A further aspect is the evaluation and comparison of the obtained data, also with respect to uncertainty, drift, etc. Using a fun experiment, it is aimed to get more students interested in the topic.

1. Introduction
Data acquisition, its implementation and practical considerations related to this topic are of major importance for engineering and consequently also for students in engineering. Together with further considerations on uncertainty and the respective evaluations these topics should build the foundation for future engineers. To our mind, it is further important to raise the awareness in students for differences in various acquisition setups and measurement system. They should further be aware that significant differences in the employed calculations and evaluations can result from the sensory equipment and measurement chain.

The considered course where this concept is applied is a laboratory course under the title of physics experiments and measurement data processing. This course is part of our Bachelor study program under the title Information Technology. This course is one of seven laboratory courses out of which the students can choose freely. These laboratory courses are to be taken at a relatively early stage of the study program and are intended to familiarize the students with the practical basics necessary for their further study. Successors of this course are, e.g., a subsequent Bachelor level course in which uncertainty evaluations and the use of the GUM [1, 2, 3] are taught [4], as well as two Master level courses: one on robust design in which we suggest the use of fault injection techniques [5], and another laboratory course where the concepts of SI units and standardization are further elaborated [6]. In the considered course, we consequently aim at introducing basic concepts of data acquisition using different sensory devices. Further, awareness on side of the students shall be raised by letting them derive the same physical quantity out of different measurement principles and comparing their advantages and disadvantages. Based on this, also the concept of traceability [7] can be discussed.

Using the considered experimental design, the students are supposed to
• Measure and acquire the IMU data, i.e. acceleration and gyroscopic data, and eventually pressure data using the wireless sensing devices which are installed inside the air rocket. Additionally, the rocket movement is also acquired using the installed cameras.
• The experiments are carried out and Newton axioms are repeated alongside using the considered setup
• The acceleration and velocity of the rocket are to be calculated along its path
• Results determined using the data from the IMU as well as video data have to be compared against each other
• The uncertainties as well as the traceability of the results can be evaluated and compared

The preliminary theory and equipment basics are introduced and explained at the beginning of each unit. At the end, the experimentally achieved results are discussed and have to be gathered in a report. Additionally, students are encouraged to give suggestions for improvement of the considered setup.

2. Rocket Experiments in Education
Rocket experiments have been found useful throughout all age groups. Such experiments are exciting for pupils as well as students and can further be used to impressively illustrate the physical effects described by Newton’s axioms. Experiments using air- or air- and water- rockets have also been used as introductory courses for students in engineering to study drag [8], the propulsion system as well as aerodynamics [9] and to give students the opportunity to realize working projects at the end of the courses [10]. In [11] a thorough analysis of such a rocket experiment and trajectory calculations for a university-level engineering course are carried out.

3. Experimental Setup and Rocket Launch Equations

![Figure 1. Measurement setup schematic illustration with air rocket, air pump, cameras and Inertial Measurement Unit (IMU).](image)

The considered experimental setup is an air rocket with integrated sensors, i.e. accelerometer, gyroscope, magnetometer. Additionally, the rocket movement is filmed with two cameras in
stereo vision (see also Fig. 1). The air rocket body with horizontal cross sectional area $A$ is filled with a commercially available air pump in order to increase the inside air pressure $p_l$ of rocket body. The ambient pressure is denoted by $p_0$. Then the force exerted due to the pressure difference is

$$F_{\text{pressure}} = (p_l - p_0)A$$

Commonly, this force is exerted homogeneously at all sides of the considered pressure vessel, here this force acts in a vertical direction, since the rocket is only free to move along the installed launch pad, which is oriented vertically.

To determine the net force acting on the air rocket, it is further necessary to subtract the weight $w_r$ of the rocket, i.e.

$$F_{\text{effective}} = (p_l - p_0)A - w_r$$

The following simplifying assumptions can be made: the length of the launch pad is small compared to the length of the air rocket body; We assume the pressure inside the rocket at launch stays constant - in reality, the pressure will be decreased with increasing volume. Under these assumptions, i.e. constant pressure and constant force exerted by the pressure, Newton’s second law (actio = reactio), here

$$F_{\text{effective}} = m_r a_r$$

with $m_r$ the rocket mass and $a_r$ its acceleration, is assumed valid and can be used to determine the rocket velocity $v_r$, acceleration $a_r$ and distance traveled $d_r$. We further have

$$F_{\text{effective}} = (p_l - p_0)A - w$$

reformulating, and using the gravitational acceleration on earth $g = 9.81 \text{ m/s}^2$, we get

$$w_r a_r = g((p_l - p_0)A - w_r)$$

To determine the acceleration, we can divide Eq. 5 by the weight $w_r$ to get

$$a_r = g\left(\frac{(p_l - p_0)A}{w_r} - 1\right)$$

With constant acceleration $a_r$, the velocity $v_r$ and traveled distance $d_r$ can be determined by

$$v_r = a_r t$$

$$d_r = \frac{a_r t^2}{2}$$

t is time. Additionally, the lift-off time can be calculated using

$$t_{\text{lift-off}} = \sqrt{\frac{2l_{\text{launch}}}{A}}$$

with $l_{\text{launch}}$ the height of the launch pad. The velocity at the vertical end of the pad $v_t$ is then given by

$$v_t = t_{\text{lift-off}} a_r$$

$$v_t = \sqrt{2l_{\text{launch}} a_r}$$

Finally, when the rocket leaves the launch pad, an additional thrust $th_{\text{start}}$ will be generated, since the pressure equalizes inside the rocket body and will stream out freely at the outlet. This thrust is small compared with the rocket weight and can be neglected in the considered setup. However, it can be determined using

$$th_{\text{start}} = \dot{m} v_{\text{air}}$$

Here, $\dot{m}$ is the air mass flow rate and $v_{\text{air}}$ is the air velocity.
4. Sensor Systems and Data Acquisition
As illustrated in Fig. 1, the sensory equipment used for the experiments as described before is, on the one hand, a camera system which is adjusted to film the movement of the rocket. On the other hand, an Inertial Measurement Unit (IMU) and, optionally, a pressure sensor (not depicted), all of which are connected to a microcontroller which provides a wireless link to a laptop (via dongle or directly). The data provided via the wireless link has to be integrated in LabView for further processing. The physical quantities of interest can then be displayed as necessary.

5. Conclusion
The presented experiment is a simple to realize laboratory setup, based on which students can be familiarized with basic physical principles such as Newton’s laws, basic principles of sensors and actuators, data acquisition, measurement uncertainty and traceability. The experimental air rocket setup is used to illustrate important points in data acquisition and comparability of measurements. The students get acquainted with sensor hardware such as accelerometers, gyroscopes, magnetometers and cameras, and the integration of the respective measurement raw data into software. Additionally, students have to convert the measured raw data into the respective physical quantity using the sensors’ calibration functions. Based on this, further calculations can be performed considering also measurement uncertainty. Thus, students are led through the whole process of measuring, going through hardware setup, software integration and data evaluation.

References
[1] BIPM JCGM 100:2008: Guide to the expression of uncertainty in measurement
[2] BIPM JCGM 101:2008: Evaluation of measurement data - supplement 1 to the "guide to the expression of uncertainty in measurement" - propagation of distributions using a monte carlo method evaluation of measurement data
[3] BIPM JCGM 102:2011: Evaluation of measurement data - supplement 2 to the "guide to the expression of uncertainty in measurement" - extension to any number of output quantities
[4] Zangl H, Zine-Zine M and Hoermaier K 2014 Utilization of software tools for uncertainty calculation in measurement science education IMEKO Joint Symposium 2014 TC1 - TC7 - TC13 Measurement Science Behind Safety and Security (Funchal, Madeira Island)
[5] Faller L M, Zangl H and Leitzke J P 2016 Fault Injection Software Tools and Robust Design Principles for Reliability and Safety in Measurement Science Education IMEKO Joint Symposium TC1 - TC7 - TC13
[6] Faller L M and Zangl H 2017 An Electromagnetic Force Balance Experiment for Measurement Science Education IMEKO Joint Symposium TC1 - TC7 - TC13
[7] BIPM JCGM 200:2012 : International Vocabulary of Metrology - Basic and General Concepts and Associated Terms (VIM 3rd edition)
[8] Jayaram S, Boyer L, George J, Ravindra K and Mitchell K 2010 Acta Astronautica 66
[9] Tomita N, Watanabe R and Nebiyov A V 2007 Acta Astronautica 61
[10] George L 2007 Engineering 100: An Introduction to Engineering Systems at the US Air Force Academy IEEE Int. Conf. on System of Systems Engineering 2007
[11] Campbell T A, Seufert S T, Reis R C, Brewer J C, Limberger Tomiozzo R, Whelan C E and Okutsu M 2016 Model rocket projects for aerospace engineering course: Simulation of flight trajectories 54th AIAA Aerospace Sciences Meeting