THE MACHINE OF BOHNENBERGER

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SCIENCE

Directional gyros and artificial horizons with their rotors suspended in two gimbals are well-known instruments in navigation. It is widely accepted that the first device showing already this kind of rotor support is an apparatus developed about 200 years ago at the University of Tübingen by Prof. Friedrich Bohnenberger. The original version of this instrument had been manufactured several times in Tübingen, and various well-preserved reproductions were additionally built during the 19th century as teaching aid for schools and universities in Europe and North America. Unfortunately, all of the initial specimens seemed to be lost since a long time, but recently one of them was discovered during a stocktaking at a grammar school in Tübingen. For this reason, the article introduces the instrument retrieved, portrays its inventor, and outlines some historical circumstances.

Figure 1 - Specimen of the Lycée Fabert, Metz, France, to illustrate the dynamic behaviour of gyros, overall height 35cm (photo: Henri Chamoux, Paris, INRP).

The Origin of the Gyroscope

Working on a simple experimental proof for the rotational motion of the earth, the French physicist Léon Foucault introduced in 1852 the term *Gyroscope* for an instrument being able to observe such movements (Foucault 1852). Besides his well-known pendulum, these investigations concentrated on gyros with cardanic suspension (Figure 1). Foucault recognised especially that a well-directed restraint of the motion of the gimbals (like blocking one degree of freedom of the suspension) leads to specific indicators detecting different rotation components (Broelmann 2002). With that, he paved the way for such important navigation instru-ments like the artificial horizon, the gyrocompass, and the directional gyro (Sorg 1976). Moreover, this was also the essential basis for the development of stabilised platforms (Magnus 1971, Wrigley 1977) leading finally into modern inertial and integrated navigation systems.

It should be added that gyros suspended by gimbals do not serve only as navigation aids. Control moment gyros are another notable application. They are employed as stabiliser for the rotational motion of mainly satellites and rarely also of ships and monorail vehicles (Mag-nus 1971, Sorg 1976). Furthermore, four of the most accurate gyroscopes ever built are used at present aboard the satellite *Gravity Probe B* in order to test Einstein's General Theory of Relativity (Kasdin and Gauthier 1996). All these examples illustrate the technical and scientific significance of the invention of gyros with cardanic suspension. Nevertheless, L. Foucault is not the originator of that mechanical principle. He was familiar with it because such gyros were especially popular in France dur-ing the 19th century: prior to the discovery of their potential as measurement device, they were already employed in numerous French schools to explain the precession of the earth rotation axis. This matter was born of the initiative of the French mathematician and politician Pierre-Simon Laplace, who recommended introducing that kind of gyros as teaching aid (Ofterdinger 1885). Figure 1 shows as an example the specimen of the Lycée Fabert, Metz, France, which was built likely between in 1860 and 1880. Here, the rotor and the two circular gimbals are enclosed by a third ring being part of the pedestal. The rotor is made of lead and

Figure 2 - Johann Gottlieb Friedrich Bohnenberger, June 5, 1765 – 19 April 1831 (oil painting of F.S. Stirnbrand, 1831).

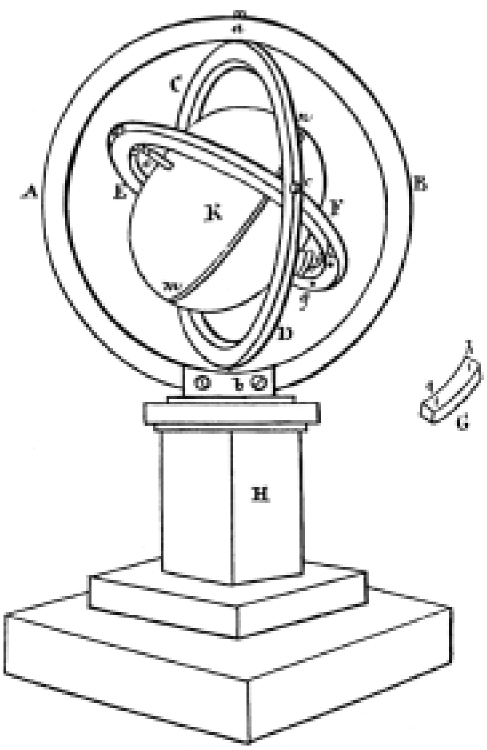

Figure 3 - Drawing of Bohnenberger's original publication describing a gyro with cardanic suspension (reference: Bohnenberger 1817).

has a diameter of 4.5cm; the overall height is 35cm.

It is likely that P.-S. Laplace referred initially to a specimen that was in possession of the École Polytechnique in Paris. This apparatus is mentioned in 1813 by one of his former stu-dents, the French mathematician S. Denis Poisson: In a paper on analysing the dynamics of rotating bodies (Poisson 1813) [1], he uses the gyro with cardanic suspension as an example, and he names the inventor of the mechanism. It was his contemporary German colleague *J.G. Friedrich Bohnenberger* (Figure 2) being Professor for mathematics, astronomy, and physics at the University of Tübingen, Germany. Using the drawing shown in Figure 3, this scientist explained for the first time the design and the use of such an apparatus (Bohnenberger 1817) [2]. Interestingly, he wrote his original description after Poisson's publication, and at this time his creation had already become quite popular. (At the moment, it is unknown to the authors how D. Poisson and P.-S. Laplace were informed about Bohnenberger's invention.) As Bohnenberger could inevitably not yet know the term gyroscope, he called the device simply Ma-chine. Therefore, the *Machine of Bohnenberger* (often less correctly named the Apparatus or Gyroscope of Bohnenberger) was the basis for Foucault's epochal work on gyros.

Comparing the details of Figure 1 and Figure 3 reveals that the specimen from Metz is only a functional reproduction. The same is true for many other variants exhibited worldwide in numerous museums and physical collections. On the one hand, this highlights once more the former popularity of the principle of Bohnenberger's apparatus; on the other hand, the ques-tion about the whereabouts of the original device arises. In his original publication of 1817, Bohnenberger indicates at the beginning that several copies of the first Machine had been manufactured in Tübingen, and at the end of the article he names the manufacturer and the prize of the Machine: All devices were assembled by the 'Universitätsmechanicus' *Johann W.G. Buzengeiger* and could be bought for 18 Gulden (roughly one monthly salary of Bohnenberger). Despite this hint, all of the initial specimens of Bohnenberger's Machine seemed to be lost since a long time.

Initiated by H. Sorg, the authors of the paper at hand searched therefore since a number of years for the original devices. Last December, during a stocktaking at a school in Tübingen, the Kepler-Gymnasium [3], A. Renz was successful and retrieved the first instrument matching essentially the drawing of Figure 3 and Bohnenberger's description. For this reason, the next two sections introduce the specimen found, portray its inventor as well as its manufacturer, and give further background information.

The Original Design and Use

Figure 4 contains a photograph of the apparatus recently found, which is now in hands of the City Museum of Tübingen. The overall height is only 16.2cm, however this agrees exactly with the statement about the size given in the original publication of 1817. The rotor symbol-ising the earth is made of ivory and has in the middle the equator *mn* of Figure 3. It is not ex-actly spherical but shows a slight flattening at the poles: the diameter of the equator is 4.5cm (the same size like the specimen of Figure 1); the poles have a distance of 4.1cm. The two gimbals and the fastening ring (outer diameter 8.5cm) are made of brass coated by a Zapon varnish. An amazing detail is the orientation of the screws close to point *b* in Figure 3, which fix the outer ring to the fastening plate. Their nicks have basically the same directions than those of the specimen retrieved.

Nevertheless, there are three noticeable differences between Figure 3 und Figure 4. The first one is the shape of the pedestal. Whereas the drawing shows a mainly quadratic cross-section with only a circular fastening plate, the stand shown in the photograph is completely round. Possibly, the draughtsman of Figure 3 has just favoured a geometry being more easily to sketch, while for manufacturing the mechanics has naturally chosen a turned wooden holder forming actually the real part. In addition, an easy change of the stand was perhaps intended as the pedestal can be pulled of from the fastening plate without loosening any screw. The second difference concerns the spool mounted on the rotor axis close to the letter *f* of the drawing (compare also Figure 5). This little drum had the function to wind up a silk thread, which served to start the rotor moving by strongly pulling this string. The real device, al-though, shows not one but two spools. Unfortunately, Bohnenberger does not mention two of such components in his papers of 1817 and 1818. On the other hand, he emphasises that a good balancing of the mechanism is very important. Therefore, a symmetrical arrangement of the little drums is natural. The last difference concerns a missing lead strip in Figure 4, which should theoretically represent the equator *mn* to increase the rotor moment of inertia. With respect to this point, the specimen shows small, but obviously old traces of violence: one of the little drums is slightly bent, and the accompanying fastening screw is distorted. Therefore, an improper repair after a rotor damage is likely.

With respect to the second difference, the draughtsman of Figure 3 has perhaps omitted the spool at point e to illustrate better that the bearings are point suspensions. For that, also the mainly covered counterpart of the conical pivot at e is indicated by the oversized brim of a bush (compare Figure 5). The bearings can be adjusted by screws

Figure 4 - The specimen found at the Kepler-Gymnasium in Tübingen, overall height 16.2cm.

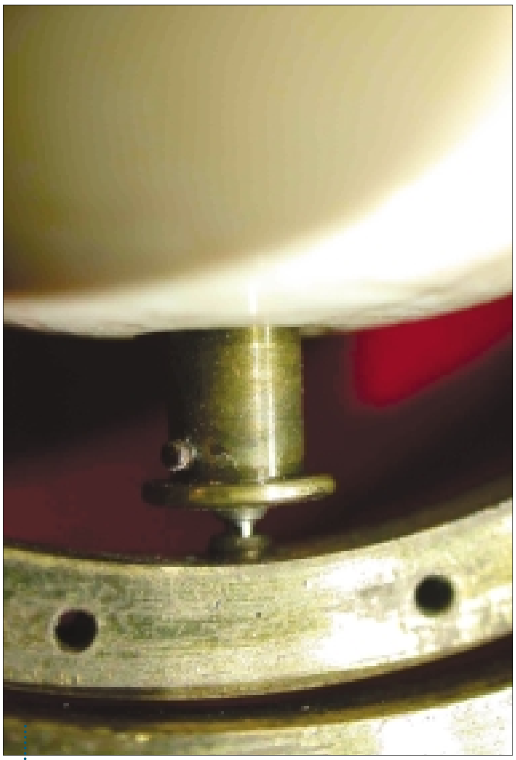

Figure 5 - Rotor bearing of the specimen found.

being orientated radial to the gimbals and the outer ring (points *a* to *f* in Figure 3). Although all pivots are made of steel, they did fortunately not begin to rust: The whole mechanism operates still very smoothly and can be even now handled as intended. Its application shall be explained next by a rather direct translation of two passages from Bohnenberger's description of 1817.

Both citations concern the direction of the axis of the spinning rotor and refer to the markings of Figure 3. The first one considers the preservation of the alignment and anticipates already the use of the directional gyro:

While the sphere is spinning around its axis, this axis will maintain permanently that di-rection which was given to it [at the beginning]. This will happen well then if one takes hold of the whole machine at its base *H* and starts moving it. While carrying around the Machine, one can move in arbitrary directions and with arbitrary velocities, and the axis of the sphere will permanently remain parallel to itself and will permanently stay aligned to north like a magnetic needle if one has, for example, orientated it at the beginning to north.

The second citation describes the demonstration of the precession of the earth rotation axis (as already mentioned):

Now, one should attach the small weight, being denoted with *G* in the figure, on the ring *EF* near the end *f* of the axis. This is done by pinning the weight using the tacks *g* and *h*, which fit into two holes being placed in the ring and being there denoted with the same letters *g* and *h*. As long as the sphere does not turn around its axis, this weight will press down the Ring *EF* at the side *F*. After some oscillations, the ring will settle only in a vertical position and, consequently, it will also take the rotation axis of the sphere to a vertical attitude. If one provides, however, the sphere with a rotational motion by means of the [silk] thread and if one aligns thereupon the [inner] ring in such a way that it is inclined at an arbitrary angle with respect to the horizon and that its weighted side is the lower one, it will be noticed that the angle of inclination of this ring and consequently also of the axis of the sphere remains constant with respect to the horizon whereas the axis no longer stays parallel to itself. It will rather move around very slowly together with the ring *CD* in a di-rection that is opposite to the direction of the rotational motion of the sphere. … Namely, it [i.e. the rotational axis] moves in a way that it describes the surface of a cone whose axis is in parallel with the direction of the disturbing force and therefore, in case of the machine described here, whose axis is vertical or perpendicular to the horizontal plane.

It has to be added here that the holes *g* and *h* exist exactly at the specimen retrieved (Figure 5). The weight *G*, however, is still missing.

Besides describing the design and the use of his Machine, Bohnenberger explains in the publication of 1817 also the reason for the precession of the gyro. He states that each particle of the rotating sphere has a momentum and tries to follow therefore initially a constant circle. If the particles, however, are subject to a disturbing force like that of the weight *G*, they are de-flected out of the planes of their tracks. The turning of the rotor axis represents simply the mean lateral movement of these deflected particles. Furthermore, Bohnenberger adds that just the rotating earth is exposed to such a disturbing force, which is caused by the combination of the oblate earth shape and the uneven attraction of the sun's gravity gradient. With this, he gives finally reasons for the cyclical variation of the stellar sky, which has a period of 25,800 years and which is caused by the earth precession.

A mathematical analysis of the phenomenon of precession is on the other hand not the intention of Bohnenberger's description. Instead, he recommends reading the paper of Poisson already mentioned (Poisson 1813). Such a reference to another publication could be interpreted as scientific routine, but it is also typical for Bohnenberger's personality and career being outlined in the next section: A certain modesty was characteristic of him, and accordingly he has never considered himself to be the inventor of his machine in a classical sense. Indeed, he based his technical design on typical suspensions of globes being very popular in the 18th century (compare Figure 2); these illustrative models showed also gimbals and were often combined with clocks or clockworks (Broelmann 2002). Nevertheless, Bohnenberger has at least recognised the importance of a fast spinning rotor, of a good balancing, and of smoothly operating bearings. Furthermore, he has for the first time described systematically the design and operation of a gyro with cardanic suspension, he has stimulated considerably the analysis of gyro dynamics, and he succeeded in making his Machine popular.

The Inventor and the Manufacturer

To illustrate his just mentioned characteristic, a translated extract from an old, comparatively immediate biography of F. Bohnenberger is helpful (Jordan 1897; other important biographies are e.g. those of Ofterdinger (1885) and especially of Reist (1965)):

The contemporaries describe him as a man of kindheartedness and benevolent attitudes. Despite many disappointments, he assumed these characteristics also with others. He was selfless and free of vanity, was of a straightforward and modest nature, was kind, and showed interest in everybody. Regardless of increasing complaints, he gave his lectures without interruption just before his death. During his good years, Bohnenberger was an excellent conversationalist, a passionate rider and marksman, a friend of hunting – anyway more an obviously active than a contemplative type.

This description is also understandable as an approach to Bohnenberger's origins: He was born on 5 June 1765 in Simmozheim, a small village close to the northern Black Forest in the dukedom of Württemberg. Simmozheim is only 4 km away from Weil der Stadt, the birthplace of Johannes Kepler, and this is not the only point of contact of Bohnenberger's life with that of the great astronomer. The father Gottlieb Christoph Bohnenberger was a Protestant priest, but occupied himself also with research in physics and engineering (much to his wife's displeasure). This was not unusual in Württemberg at that time: The inventor of a pioneering calculator and other devices of precision mechanics, Philipp Matthäus Hahn, is a prominent contemporary example; and such a career was also given to F. Bohnenberger: Educated at first by his father, he showed early a particular talent in mathematics, physics, astronomy and geodesy. Later on, he went to a grammar school in Stuttgart from 1782 to 1783 and was then admitted to the *Tübinger Stift*. This is a college of Protestant theology in conjunction with the University of Tübingen. It was founded in 1536 and is still existing (see Figure 6). Among its graduates are many personalities who influenced significantly the German and European history like J. Kepler or the philosopher G.W.F. Hegel, who was a fellow student of F. Bohnenberger. The theological education was still a prerequisite for Bohnenberger's later occupation as a high-qualified teacher; nevertheless, his interest in this subject was moderate. On the other hand, mathematics and physics were at that time also part of the syllabus in theology, and the young student absorbed these subjects hungrily. Simultaneously, he got at the Tübinger Stift a sound access to the intellectual world of his epoch.

F. Bohnenberger passed his exam as a priest in 1789 and became after that a curate in the new parish of his father in Calw-Altburg in the northern Black Forest. This second phase in the parental home initiates his later scientific work: On the side, he occupied himself with astronomy as well as with cartography and presented in 1793 a detailed manuscript on creating a map of Württemberg to the duke of Württemberg. Thereupon, the prospective scientist won a scholarship enabling him to continue his education at the observatory of Gotha and the University of Göttingen from 1793 to 1795 and to publish his first book (Bohnenberger 1795). In 1796, he became assistant at the observatory of the University of Tübingen; in 1798, the duke of Württemberg promoted him to a professor for mathematics. With that, Bohnenberger got the position for his life, where he could develop his talent to the full. In the same year he married also his wife Philippine, who bore him two daughters and two sons.

Figure 6 - Current view of the upper old city centre of Tübingen: No. 1: North-East Tower of the castle, No. 2: Tübinger Stift, No. 3: former main building of the University, No. 4: house of Buzengeiger's workshop (photo: the City of Tübingen).

To illustrate the locality, which was from now on the centre of Bohnenberger's work, Figure 6 gives a view of the upper urban centre of Tübingen, which kept its medieval townscape until today. The North-East Tower of the Castle of Tübingen accommodated the observatory of the University from 1752 to 1955 (Figure 7) as well as partly the lecture hall of mathematics and physics. Within only a few minutes, Bohnenberger could moreover reach the other buildings of the University as well as the workshop of J. Buzengeiger (see below). In 1803, he and his family moved also into a flat within the eastern wing of the castle.

With these conditions, the young professor began a long, very produc-

Figure 7 - The North-East Tower of the Castle of Tübingen before dismantling the observatory in 1955 (photo: the City of Tübingen).

tive scientific phase. His first task was to consolidate and to extend the observatory. In parallel, he continued his work on publishing the map of Württemberg. This occupation and his lectures stimulated in turn the expansion of his mathematical methodology as well as the development of devices for geodetic measurements and physical experiments. In several textbooks and many scientific papers, he documented this activity (Reist (1965) has compiled a detailed publication list). Within the scope of the paper at hand, it is however only possible to outline the most impor-tant topics:

Geodesy: This is the area where Bohnenberger made the most important contributions. The elaboration of his map of Württemberg was the first topographical recording of that entire region. Using the observatory of the University as zero point, he covered Württemberg with a triangulation net utilising mainly astronomical observations and trigonometric measurements. His main instrument was initially the sextant leading later on to Bohnenberger's development of a repetition theodolite. In addition, he used barometers for measuring heights and an artificial mercury horizon. He invented also the reversible pendulum (seven years before Henry Kater created it independently for the second time) to determine the local gravity, and he wrote presumably the first textbook in higher geodesy (Bohnenberger 1826). The political reform of Europe at the beginning of the 19th century (due to Napoleon's wars and the Con-gress of Vienna) resulted in a major expansion of Württemberg, which became furthermore in 1806 a kingdom. This change required a thorough survey of the new territory. In 1818, Boh-nenberger was given the responsibility for that task becoming his primary achievement [4].

Astronomy: During his early scientific phase, Bohnenberger concerned himself mainly with astronomy. Already in 1786, he obtained attention for observing a sun passage of the planet Mercury. Preparing his work in geodesy, he elaborated a comprehensive procedure on the geographical position finding by astronomical observations. This practice was documented in his first book (Bohnenberger 1795) achieving a large circulation. It included the construction of a quadrant and a sextant as well as instructions to compensate errors of astronomical instruments. He developed also a telescope ocular with illuminated cross hairs, the eyepiece of Bohnenberger. In 1811, he published an extensive textbook on astronomy (Bohnenberger 1811a), in which he deals with the apparent motion of the celestial bodies. The invention of his Machine is part of this context.

Physics and meteorology: Motivated by the development of his instruments for geodesy and astronomy as well as by the scientific work of his father, Bohnenberger researched in a broad spectrum of physics and meteorology. Investigations about hygrometers, thermometers, and hydrometers, about the properties of water, and about measuring the angles of crystals are examples. His work on electrostatics is especially well-known through the invention of an electroscope and an electrostatic induction machine. His lectures in experimental physics were very popular as he was an extraordinarily talented experimenter.

Mathematics: Just like his courses in physics, the lectures in mathematics stand out due to clarity and thoroughness. He taught algebra, geometry, plane and spherical trigonometry, practical mathematics, as well as differential and integral calculus. The last subject is documented in Bohnenberger's third textbook (Bohnenberger 1811b) using a rather modern formulation. Finally, it should be mentioned, that Bohnenberger corresponded several times with Carl Friedrich Gauß, who appreciated his colleague from Tübingen very much.

In the face of his high productivity, it is hardly surprising that F. Bohnenberger received numerous honours. He got early offers of other professorships from Freiburg, Germany, St. Petersburg, and Bologna as well as an offer to join the general staff of the Austrian army. He was member of academies of sciences in Göttingen, Munich, Berlin, and, as an exceptional mark of respect, in Paris. The University of Marburg awarded him an honorary doctorate in medicine, and in 1818, he was given a peerage by the King of Württemberg. Moreover, the president of the *Confederation of the Rhine*, a union of 16 German principalities from 1806 to 1813, awarded him with a golden medal especially for his Machine. (This was interestingly before Bohnenberger's original publication from 1817.)

In contrast to that, his own University caused F. Bohnenberger various problems. He got for example his full academic rights only 18 years after his appointment as an professor. He could also not establish special curricula for natural sciences or engineering and had no PhD students. Instead, he had to educate students of theology, who completed their studies with mathematics or physics as a subsidiary subject. Moreover, the profession as a land surveyor was not regarded as an academic activity, but as a simple "measuring of angles and calculating of sine and cosine". That discrepancy had two reasons. The first one was the jealousy of Bohnenberger's continuing support by the rulers of Württemberg, who recognised the economic importance of his work. The second reason resulted from the fact that faculties for natural sciences or engineering were not yet known at German universities: Bohnenberger was member of the faculty for philosophy, and his colleagues did not understand his work. (At best, they tried to assess the style of his Latin publications.)

This conflict is especially worth mentioning because of two aspects. Firstly, it highlights how disesteem and speechlessness caused humanities and natural sciences (together with engineering) to drift apart at the beginning of the 19th century. Secondly, a student of F. Bohnenberger realised particularly this situation. It was the crown prince of Württemberg, who became later on in Stuttgart *King Wilhelm I* and who established in 1863 at the University of Tübingen the first German faculty for natural sciences.

The controversies at his University, the early death of his wife in 1821, and the exhausting work as a land surveyor ruined gradually Bohnenberger's health. He suffered increasingly from a heart condition and died on 19 April 1831 just after a lecture at an age of 65 years.

Citing C.F. Gauß, this meant an important loss for science. It affected especially J. Buzengeiger, who was more than the producer of the Bohnenberger's Machine. Being both an exceptionally skilled craftsman and talented designer, he had become a congenial partner and friend of F. Bohnenberger during a long-lasting cooperation. Although there are only a few documents about his work and his personality, it is possible to outline his life (NNdD 1835):

J. Buzengeiger was born on 25 June 1778 in Tübingen and grew up in very poor circumstances. Additionally, he was from childhood in poor health. At an age of about 14 years he moved to Kornwestheim (near Stuttgart), where he went through an apprenticeship as a watchmaker. Afterwards he was employed as a journeyman in Esslingen and Güglingen (also near Stuttgart) as well as in Ansbach (near Nuremberg), where his older brother Karl was a teacher for mathematics. (Karl Buzengeiger became later on professor for mathematics at the University of Freiburg, Germany.) In Güglingen he found also adoptive parents, who helped him out of a heavy illness and who enabled him to establish an own workshop. Supplemented by Buzengeiger's brother, his new parents educated him also in mathematics. In 1803, Buzengeiger returned to Tübingen. Two years later he married, and at the same time he was employed as a probably free-lance mechanics at the University (compare also Figure 6).

Caused by his complaints, especially headache, Buzengeiger was not able to sleep more than four to five hours a night. Therefore, he stayed often already at two o'clock in the morning in his workshop and devoted himself to his electrical, optical or mechanical instruments like telescopes, barometers, pumps, scales, clocks, sextants, and planetaria. He manufactured for the professors of the University of Tübingen countless, various devices for science and lec-tures. Moreover, Buzengeiger, who was in principle an autodidact, enhanced with this his broad knowledge in mathematics, physics, and chemistry. His relationship with F. Bohnen-berger was particularly intensive; he participated in astronomic measurements as well as in discussions in scientific journals (Buzengeiger, 1831). Despite his health problems, he had also a similar modest, kind, and sociable nature. He could merely not bear if someone touched his instruments clumsily.

Over the years, the high quality of Buzengeiger's devices became internationally well-known. He supplied universities and schools in Germany, Switzerland, Denmark and Russia as well as the Royal Society in London with physical instruments. Interestingly, he was able for this to prepare his products in a way that even mercurial barometers could stand the necessary long overland transports. He participated in 1812 in the first trade fair of Stuttgart and was decorated with a medal by the King of Württemberg in 1826.

J. Buzengeiger survived his scientific partner only five years. He died on 26 October 1836 and left his wife considerable assets. Operated by one of his former apprentices, his workshop existed for about further twenty years until it was closed. Another of his learners, C.H. Erbe, founded in 1847 an own business, which became a still existing, worldwide operating company for medical technology. Therefore, not only the heritage of F. Bohnenberger continued to live, but also that of J. Buzengeiger.

Epilogue

In the course of preparing the paper at hand, the authors succeeded in clearing up some details concerning Bohnenberger's Machine. For example, the current head of Erbe's company reported recently the place of Buzengeiger's workshop. Many questions, however, are still open: How many specimens of the apparatus were assembled, and who acquired them? When did J. Buzengeiger especially manufacture the first Machine at all? Did he use constructional drawings? By which way did Laplace and Poisson hear about Bohnenberger's invention? What is the year of manufacture of the specimen retrieved and when did the school in Tübin-gen gain possession of it? Do other specimens still exist?

It is hoped that this publication reaches some readers who have additional knowledge about the Machine of Bohnenberger. The authors would appreciate any useful information.

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Notes

[1] For this, D. Poisson used the gyro equations and the angles of Euler as well as already a similar notation like modern textbooks.

[2] One year later, Bohnenberger issued a second, slightly revised version of his manuscript with a somewhat dif-ferent drawing (Bohnenberger 1818, Sorg 1976).

[3] A gymnasium is a German school type between a college and a high-school or similar to a grammar school.

[4] A dead straight avenue northwest of Stuttgart forms the most visible trace of this survey: Connecting the castle Solitude with the City of Ludwigsburg, this street bears the geodetic baseline having a length of about 13,032m.

Biography of the Authors

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Jörg Wagner is professor for Adaptive Structures at the Institute for Statics and Dynamics of Aerospace Structures, University of Stuttgart. His scientific interests are inertial, satellite and integrated navigation systems, test procedures, dynamics of aerospace structures, and biomechanics.

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