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The Kibble balance of the Ultrasound Laboratory of Inmetro

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ABSTRACT
The 2019 redefinition of the International System of Units (SI) established the kilogram based on the Planck constant, eliminating reliance on a physical artefact and significantly enhancing mass metrology. The Kibble balance is one of the key experiments enabling this realization, linking mass measurements to fundamental electrical standards. This work presents a cost-effective Kibble balance prototype developed at Inmetro's Ultrasound Laboratory (Labus), designed using 3D printing and controlled via a Raspberry Pi microcontroller. Experimental results demonstrate the feasibility of using simplified Kibble balances for metrological applications, achieving mass measurements from 100 mg to 600 mg with a relative uncertainty of 7 %. Future developments will focus on sensor calibration and mechanical stability improvements to further enhance accuracy and precision.

Section: RESEARCH PAPER

Keywords: Kibble balance; metrology; 3D printer

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1. INTRODUCTION

The International System of Units (SI) has been evolving and changing with the development of new technologies. In May 2019, the SI was revised by the Bureau International des Poids et Mesures (BIPM). One of its consequences was the redefinition of the kilogram, one of the seven base units of the SI, which, as of May 20, 2019, is based on a physical constant, the Planck constant.

Before the SI revision, the kilogram was the last base unit still defined by a material artifact, known as the International Prototype of the Kilogram (IPK) [1].

The IPK was manufactured in 1879 and sanctioned in 1889 by the first General Conference on Weights and Measures (CGPM) meeting. This artifact is made of a platinum-iridium alloy (90 % platinum and 10 % iridium) with a diameter and height of approximately 39 mm, housed at the BIPM in Paris, France [2].

During the periodic check between the IPK and its official copies, drifts of about 50 µg over 100 years were identified, indicating a possible lack of long-term stability of the reference standard [3].

In the revised SI, a fixed value of the Planck constant, h, is used to establish the unit of mass. There are currently two methods for determining the relationship between the mass and the Planck constant h: the Kibble balance [4], [5] and the X-ray crystal density method [6].

Before the SI revision, small masses could only be related to 1 kg through a series of subdivisions, and, at each subdivision stage, the relative uncertainty is increased. The SI redefinition allowed mass to be realized directly at any nominal value and any location using an appropriately scaled instrument, allowing measurements to be taken in a research lab or a production environment [7].

This whole process of revising the SI gave prominence to the measurement system that helped in the redefinition of the kilogram, and the use of the Kibble balance. Previously known as a watt balance, the Kibble balance was invented at the National Physical Laboratory (NPL) by Bryan Kibble [5] in 1975 and indirectly compares electrical power and mechanical power, measured in units of watts (hence the term “watt balance”) [8].

Dr. Kibble passed away in 2016, and the watt balance technique is now referred to as the Kibble balance technique in his honour. Originally, it was intended to be used as a substitute for the current balance that defined the ampere in terms of mechanical units, [9], [10]. When combined with the electrical resistance, derived from the calculable capacitor [11], the Kibble balance can be used to realize the volt or ampere concerning the kilogram [12].

Over time, several National Metrology Institutes (NMI) developed versions of the Kibble balance to assist in the redefinition of the kilogram. One of these balances was the bench-top Kibble balance, which, despite not showing the accuracy and precision of a NMI Kibble balance, uses the same physical principle in its measurements. In this work, a balance developed at Inmetro's Laboratory of Ultrasound (Labus) is described. The device was built with 3D printed parts and with the aid of a Raspberry microcontroller and Python programming language.

2. HOW DOES THE KIBBLE BALANCE WORK?

There are different kinds of Kibble balances. They differ mainly in the details of their construction, such as the size, mechanisms used to move the coil, mechanisms used to measure the mass and other details [13].

The balance used as a reference for the development and construction of the Labus Kibble balance was based on an equal arm balance. Figure 1 presents a drawing of the Kibble balance of Labus.

The original Kibble balance has two modes, the force mode and the velocity mode [9]. The velocity mode is based on the Lorentz force principle. A coil (wire length L) is moved at a vertical speed through a magnetic field (flux density B), inducing a voltage V in the coil. Figure 2 and Figure 3 show the coil in velocity mode and force mode.

The induced voltage (V) is related to the velocity (v) through the flux integral $B\,L$. According to Faraday's law of induction, the magnitude of the induced voltage is given by (1):

$$V = B\,L\,v\,. \tag{1}$$

Similarly, force mode is also based on Lorentz forces. In the force mode, the gravitational force on a mass (m) is balanced by the electromagnetic force (F_e) generated by a current (I) carried in the coil of wire length L immersed in a magnetic field with flux density B. In the force mode, the electromagnetic force is given by (2):

$$F_e = B\,L\,I = m\,g\,. \tag{2}$$

The flux density B and the wire length L are difficult to measure accurately; thus, velocity mode is necessary as a

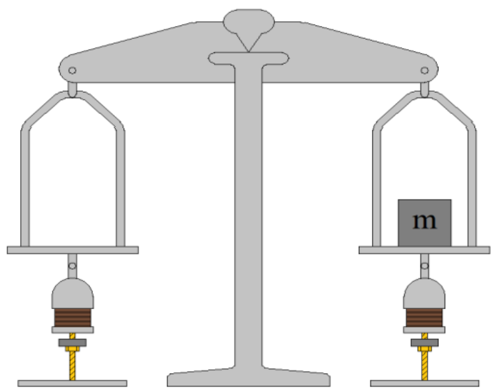

Figure 1. Illustration of Labus bench Kibble balance.

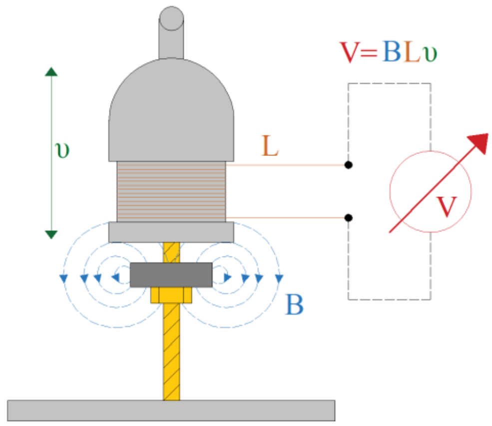

Figure 2. The coil in velocity mode.

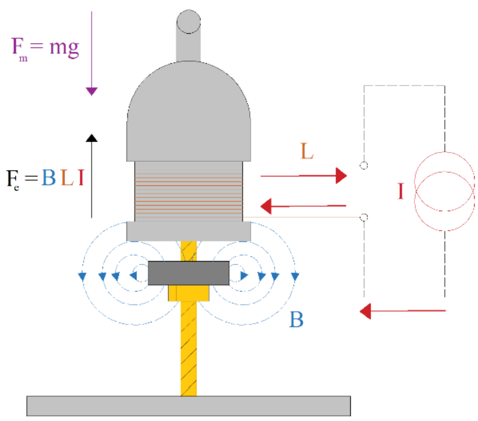

Figure 3. The coil in force mode.

calibration technique. Combining Equations (1) and (2), the $B\,L$ factor is nullified. So, rearranging the variables, a solution for mass is obtained according to (3):

$$V\,I = m\,g\,v \Rightarrow m = \frac{V\,I}{g\,v}\,. \tag{3}$$

Then, with velocity mode and force mode, it is possible to relate the electrical power $V\,I$ and the mechanical power $m\,g\,v$, both measured in watts (origin of the name).

3. PROTOTYPE DESCRIPTION

There are many ways to construct a Kibble balance. Due to easy construction, an equal-arm beam balance was chosen, in which, on each side, a weighing pan is suspended. Below each weighing pan, a coil is connected and immersed in a radial magnetic field generated by two magnets.

An equal-arm beam balance was selected due to its straightforward mechanical design, reduced sensitivity to asymmetries, and ease of construction using 3D-printed components. This configuration ensures a balanced distribution of forces, minimizing systematic errors that could arise from mechanical misalignment in more complex balance structures.

The parts were printed in PLA Filament with different densities, varying from 20 % to 80 %, according to each part's need for mechanical strength. The support base of the balance and the vertical structure that supports the balance arm were printed with a density of 80 %, due to being parts that concentrate greater mechanical effort. In Figure 4, a picture of the balance can be observed.

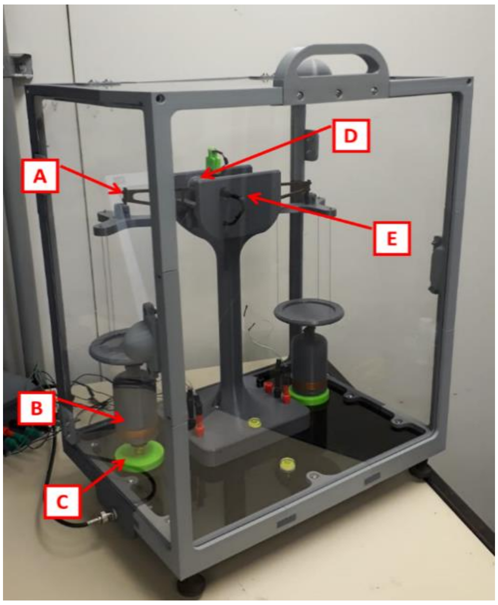

Figure 4. Prototype of the Labus Kibble balance, showing key components: (A) Equal-arm beam providing mechanical stability, (B) Coil used in electromagnetic force compensation, (C) Magnet assembly generating the required magnetic field, (D) Shadow sensor detecting balance displacement, (E) Line laser for precise position tracking.

A pair of neodymium magnets (N35) are fixed vertically, on both sides of the balance, by brass screws supported by a 3D printed base, to generate the magnetic field. Brass nuts are used to restrict the repulsive force of the magnets, also defining their separation distance, as they are placed in the repulsive orientation. This design allows the adjustment of the distance between the magnets and the geometric centre of the magnetic assembly.

The coil was wound by hand with the aid of an electric screwdriver. Each coil has approximately 3,000 turns of AWG-36 copper wire, obtaining a final resistance of approximately 500 Ω.

Laser modules (dot and line lasers) and a shadow sensor were mounted on the balance structure to monitor the movement of the balance and the coil position. On one side of the balance arm, a linear laser is directed toward a shadow sensor, fixed on the other side of the balance arm, so that the arm partially obstructs ≈ 50 % of the light when the balance is in the zero position. When the scale tilts, the shadow sensor receives more or less light depending on the direction of the tilt. In Figure 5, it is possible to observe the shadow sensor and the linear laser responsible for monitoring the balance's position.

The point laser is used as an optical lever used to characterise the shadow sensor. The laser is mounted on the top of the arm pointing to the scale of the ruler attached to the wall.

For control and monitoring the balance, a Raspberry Pi 3 microcontroller, model B+, an oscilloscope, model DSO-X 3012A (Agilent Technologies, USA), and two 4-channel relays are used.

The Raspberry Pi was chosen as the main control unit due to its versatility, low cost, and ease of integration with sensors and measurement instruments. Its ability to handle real-time data acquisition and control relay switching between measurement modes makes it a practical alternative to more expensive dedicated controllers. The oscilloscope channels are used to obtain the balance position by reading the shadow sensor and measuring the voltage induced in the coil in velocity mode, or the

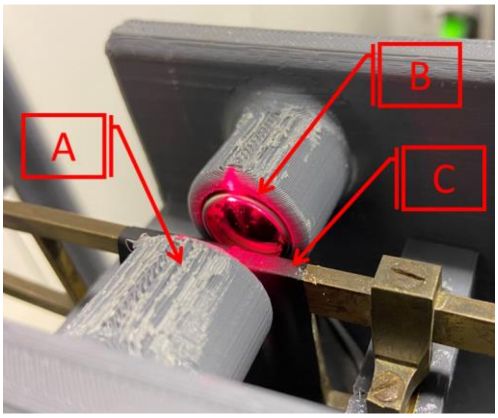

Figure 5. Shadow sensor and lasers are used to monitor coil position. A – Linear laser used to calibrate the coil position; B – Photodiode used as a shadow sensor to monitor the coil position; C – Arm-beam.

current applied to the coil, in force mode. The oscilloscope function generator is used to apply a sinusoid in the actuator (coil that generates the sinusoidal movement) in velocity mode, to produce the oscillatory movement with a velocity of around 2 mm s^{-1}. The generator is also used for applying a DC signal to the coil in force mode. The relays are controlled by the Raspberry GPIO ports and are responsible for change between the measurement in velocity mode or force mode. The relays are also responsible for selecting the coil used in the measurements (coil A or coil B). Finally, also through the Raspberry GPIO ports, the point laser and line laser are switched on or off.

For the development of the balance control and monitoring application, the Python v3.7 programming language was used. The following libraries were used to develop the application: tkinter, matplotlib, numpy, pyvisa, sympy, scipy and sklearn. The developed application is embedded in the Raspberry, controlling its GPIO ports and communication with the oscilloscope. The application allows the shadow sensor to be calibrated using the point laser and the graduated scale fixed on the wall, generating a curve that relates the indication of the shadow sensor with the position of the coil. The application also configures the signal characteristics applied to the actuator in velocity mode, such as amplitude and frequency. In addition, all graphs are generated by the software and the estimates of the $B\ L$ factor, in velocity mode $(B\ L)\ v$, and mass and their respective measurement uncertainties.

4. RESULTS AND DISCUSSION

The balance needs to be aligned and adjusted before performing any measurements to provide consistent results. The adjustment process is necessary to establish a relationship between the output voltage of the shadow sensor and the coil

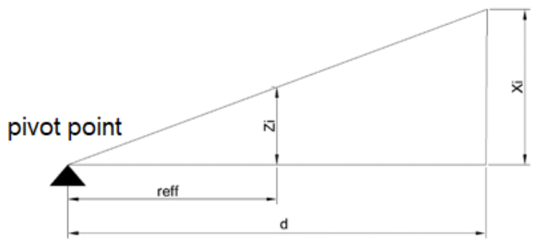

Figure 6. The scheme used to estimate coil height by trigonometry.

position (z). The coil position can be estimated by trigonometry, as shown in Figure 6.

For this, the point laser is directed at the wall, where a scale is attached. The distance from the pivot point of the balance arm to the wall (d) and the distance from the pivot point to the coil suspension point (r_{eff}), that is, half the length of the equal arm, were measured, which were approximately 258 cm and 13.5 cm, respectively. Then, the initial position x_0 of the point laser, indicated by the graduated scale fixed on the wall, is informed to the control application of the Kibble balance and the other x_i positions, indicated for the other positions of the balance arm. In this way, the position of the coil can be estimated according to (4).

$$z_i = \frac{\Delta x_i}{d} r_{\mathrm{eff}} \,. \tag{4}$$

At the end of the measurements of different positions of the balance arm, the application developed in Python calculates a regression to determine the behaviour of the shadow sensor concerning the variation in the height of the coil. In Figure 7, it is possible to observe the regression calculated by the application.

It can be seen, in Figure 7, that the shadow sensor has a linear behaviour, with a coefficient of determination (R^2) of 0.9978, which demonstrates that the model fits well with the data. It is also possible to observe the equation that correlates the coil position with the shadow sensor indication and the expanded uncertainty (U = 0.06 mm, k = 2.17, p = 95 %), represented by the shaded band around the linear regression.

With the definition of the relationship between the indication of the shadow sensor and the vertical position of the coil, it is possible to start the velocity mode to determine the factor $(B\ L)\ v$. It was decided, arbitrarily, to use coil A to generate the oscillatory movement (driver) and coil B as a measuring coil. Therefore, a sinusoidal signal was applied to coil A to generate an oscillatory movement and determine the factor $(B\ L)\ v$ of coil B. A sinusoidal signal of 0.8 Hz frequency and 100 $\mathrm{mV_{pp}}$ amplitude was used, a configuration that produced the best results, which means a better fit to the linear regression used to determine the $(B\ L)\ v$ factor.

The shadow sensor and voltage induced in the coil signals are acquired, during approximately 18 seconds, from the oscilloscope, through the developed application. The application uses the results obtained in the previous step to determine the behaviour of the shadow sensor, to convert the voltage signal from the shadow sensor to a signal of the position of the coil.

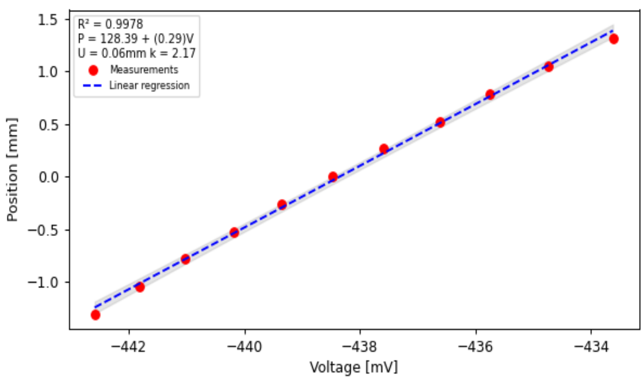

Figure 7. Linear regression that determines the correlation between the coil position and the shadow sensor indication.

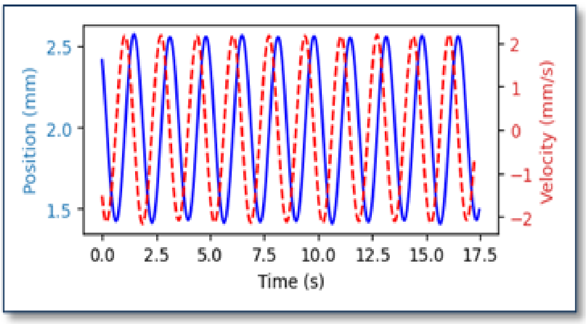

Figure 8. Signals obtained in velocity mode (blue: coil position; red: coil velocity).

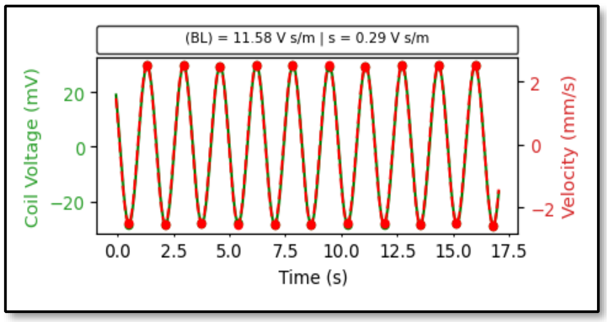

Figure 9. Velocity signal (red) and coil voltage signal (green).

Afterwards, the signal obtained from the oscilloscope regarding the variation of the position of the coil is derived in relation to time to obtain the signal regarding the speed of the coil. Therefore, from the signal referring to the variation of the coil velocity, it is possible to calculate the factor *(BL)v*, which is the ratio of the voltage induced in the coil to the coil velocity.

Figure 8 shows the coil position and the coil velocity signals, and Figure 9 shows the signals of the voltage induced in the coil and the speed of the coil.

It is also possible to observe, in Figure 8 and Figure 9, the average value of $(B\ L)\ v$ = 11.58 V s m^{-1} and its respective standard deviation, calculated by dividing the average value of the voltage induced in the coil by the average velocity of the coil. The factor $(B\ L)\ v$ was calculated by the average of the values indicated by the red dots (speed values) and by the average of the values indicated by the green dots (values of voltage induced in the coil) (red dots underwrite green dots).

Finally, a graph is generated by plotting the voltage induced in the coil in relation to the coil velocity, Figure 10. The factor $(B\ L)\ v$ can also be determined by the slope of the line obtained

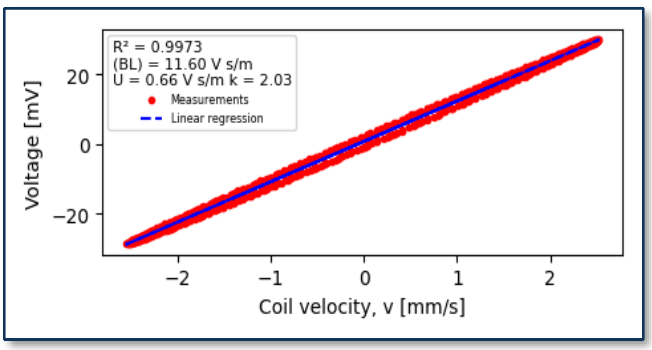

Figure 10. Linear regression was calculated to determine the $(B\ L)\ v$ factor.

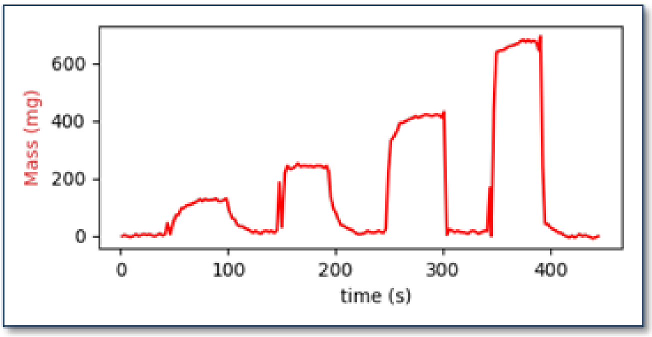

Figure 11. Mass indication in kibble balance

Table 1. Result of mass measurement in force mode.

Reference	Average	Bias	Uncertainty
107 mg	112 mg	5 mg (5 %)	15 mg (14 %)
217 mg	218 mg	1 mg (0.5 %)	20 mg (9 %)
377 mg	404 mg	27 mg (7 %)	28 mg (7 %)
632 mg	667 mg	35 mg (6 %)	43 mg (7 %)

by linear regression (R^2 = 0.9973), in the case of this work $(B\ L)\ v$ = 11.60 V s m^{-1} (U = 0.66 V s m^{-1}, k = 2.03, p = 95%). The application considers the $(B\ L)\ v$ factor obtained by the linear regression slope on the next steps.

After determining the factor $(B\ L)\ v$ the force mode can be executed. However, before carrying out the mass measurement using the force mode, it is necessary to put the balance in equilibrium, which means carrying out the "tare". In this way, when clicking on the "tare" button in the application, a DC signal is applied to coil B (weighing coil) until the shadow sensor indicates that the balance is in equilibrium. So, the current required to maintain it in equilibrium is recorded to be subtracted at the time of weighing. After "tare", the balance is ready to perform the mass measurement.

Four masses (107 mg, 217 mg, 377 mg and 632 mg) were measured to illustrate the operation of the balance in force mode. In Figure 11, the graph of the indication of mass as a function of elapsed time is shown.

The average of ten observations, the measurement bias and the expanded measurement uncertainty for a coverage probability of 95 % and a coverage factor of 2.05 can be found in Table 1.

As can be seen in Table 1, the Labus Kibble balance can measure a mass range of 100 mg to 600 mg with a maximum bias of 7 % (mass 377 mg), and a maximum expanded uncertainty of 14 % (mass 107 mg), which can be considered a reasonable preliminary result, given the balance is built with 3D printed parts, that are produced in plastic, and no care regarding environmental influences had been taken so far.

The main source of uncertainty identified, which contributes about 50 % to the final uncertainty, concerns the regression curve performed in the shadow sensor calibration. In order to reduce it, more points could be acquired to generate the curve, but other studies have been performed to better understand the whole process.

5. CONCLUSION

The prototype developed at Inmetro's Laboratory of Ultrasound demonstrated the feasibility of constructing a Kibble balance for gram-level measurements. The measurement uncertainty obtained was considered satisfactory for the first approach, given that the prototype was built using 3D-printed plastic components. As this is the first version of the Kibble balance, further improvements will be implemented to reduce measurement uncertainty and bias.

Beyond its primary objective, the development and construction of this balance also provided valuable insights into critical factors affecting measurement performance. In addition to key variables such as voltage, current, gravity, and velocity, other elements were identified as significant contributors to measurement bias and uncertainty, including mechanical stability, the magnetic system, and knife-edge friction. The Kibble balance remains under development, with ongoing modifications aimed at enhancing accuracy and precision.

This study highlights the potential of simplified Kibble balances for practical metrology applications, particularly in environments where high-end precision instruments may not be readily available. Future improvements will focus on refining mechanical stability, optimizing the magnetic field configuration, and integrating advanced calibration techniques. Beyond laboratory applications, this approach could also be valuable for educational purposes, offering students and researchers a hands-on tool to explore precision mass measurements based on fundamental physical principles.

AUTHORS' CONTRIBUTION

R.C. Mayworm: Conceptualization, Methodology, Software, Investigation, Resources, Data curation, Writing – original draft. **E. Webster:** Resources, Visualization. **A.V. Alvarenga:** Conceptualization, Software, Investigation, Data curation, Visualization. **S. Davidson:** Supervision, Project administration, Data curation. **R.P.B. Costa-Felix:** Writing – original draft, Supervision, Project administration, Funding acquisition.

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