Prototyping a Mechanical Mounting System for the Photogrammetric Use of USB Microscopes

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Abstract. The widespread and diversified use of portable devices with high magnification power at relatively low-cost, i.e., the so-called USB digital microscopes, has revealed the possibility of employing their photographic output in Structure from Motion processes for sub-millimetric digitisation. However, USB microscopes, born for two-dimensional inspection – if used without specific accessories, designed *ad-hoc* for the photogrammetric capture phase – can pose some difficulties for the surveyor in managing capture operations. Thus, this study suggests prototyping a low-cost, complete, and portable mounting compatible with the most common USB microscopes for image scanning. This system makes it possible to use portable USB microscopes for three-dimensional modelling at a low-cost, as it is easy to replicate both in terms of construction and the materials used. Therefore, through the interaction of several skills, the work shows how the photogrammetric process can also be made accessible to devices that were not initially designed for such application, paving the way for new paths in representation engineering research.

Keywords: Structure from Motion · Additive Manufacturing · Fast Survey

1 Towards the Micro-photogrammetric Use of USB Microscopes

For those requesting to produce and disseminate digital models of small items, particularly concerning sub-millimetre resolution applications, there is an ever-increasing need for accessible, efficient, and reasonably priced three-dimensional acquisition systems.

Although the large-scale dissemination of digital photography and its photogrammetric applications can provide a successful response, close-range activities have only

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recently gained recognition; therefore, to date, the appropriate applications for the rigorous description of small objects and their 3D virtual representation (digitisation) are still being studied and explored [1]. This could be due to the inherent difficulty of obtaining the expected result with known alternatives – such as photogrammetry – which are relatively cheaper than less versatile techniques. Indeed, CMM systems, laser triangulation, conoscopic holography, interferometry, X-ray computed axial tomography, confocal microscopy, etc. [2, 3], are generally unaffordable equipment being developed in highly specialistic fields, e.g., for applications in dimensional inspection, quality control, industrial design, testing, and reverse-engineering of micro components [4].

However, the image-based alternative requires a not negligible technical rigour. The challenges that 'very' close-range photogrammetry poses to the surveyor have recently been regarded as inherent in customising dedicated accessories to ensure adequate and verifiable accuracy, precision, and an optimised process [5–7]. Some of the primary studies available in the literature [8–15], dealing with the acquisition of small objects with necessarily high levels of detail and accuracy (hundredths and tenths of a millimetre, respectively), focus on streamlining photogrammetric workflows while maintaining high metric reliability [11]. Namely, these studies focus on adopting different solutions based on camera stabilisation, rotating bases, coded targets and greater control of camera settings and lighting, highlighting improvements in model quality, and emphasising the advantage of more controlled protocols.

Therefore, if these expedients significantly improve the outputs[1], they can make a significant difference in the case of more entry-level devices. Furthermore, it would mean that the design of *ad-hoc* configurations for a series of new photographic devices – now available on the market at affordable prices – could potentially allow for their incorporation into complex photogrammetric processes.

Thus, alongside the widespread use of compact and lightweight cameras[2], we now find another type of portable and affordable device in the panorama of macro-photography [13, 14]. Said devices are USB portable microscopes – created for inspection and two-dimensional metrological analysis – and are already popular in the manufacturing industry for quality control and in the medical field [16]. They consist of small, handy optical zooms designed to display image output directly on the monitor. Despite their resolution (usually up to 5MP) and small sensor size (about 1/4″), the images produced are to be considered high quality for the commercial segment in which they fit. However, not being designed as instruments for image-based three-dimensional reconstructions, these USB microscopes – albeit simple and intuitive – can be pretty challenging to use. Due in part to the absence of accessory components, such as mounts and calibrators, to adapt them for photogrammetric purposes, applications concerning the use of USB portable microscopes for three-dimensional reconstructions of the entire volume of a test specimen are sporadic. Less unusual, however, are partial modelling of objects whose two-dimensionality is prevalent [17].

[1] In the case of instruments whose effectiveness is 'established' for good quality macro-photogrammetric results, such as when using full-frame cameras combined with macro optics.

[2] In addition to the single-board computers which are around the size of a credit card (Raspberry Pi) and can be combined with both entry-level and professional photographic sensors and optical bodies.

The literature offers a few examples of the imaged-based set-up design involving USB microscopes.

In 2011, Graham proposed a 2D vision-based measurement system to convert USB microscopes, which were still considered hardly more than toys, into metrological tools [18]. This study takes a step forward in the metrological use of the instruments but proposes a set-up applicable only to two-dimensional measurements.

Subsequently, Maté-González et al. [19] conducted a micro-photogrammetric characterisation of cut marks on bones from USB microscope captures. Although it is not specified which mounts and systems were used for the acquisitions, this study demonstrates that the converging capture scheme increases the quality of the models, albeit they were excessively noisy and of poor quality. At the same time, Zitek et al. [20], using an Arduino Uno controller board, a stepping motor, and a self-designed 3D printed stage, stabilised the microscope while enabling a 360-degree rotation of the object, thus clarifying how to structure an inexpensive system (360 euros) to obtain convergent captures of objects smaller than 1 cm. However, their tests involved using a common stand that allowed the microscope to be held at a single fixed angle for the entire rotation; therefore, there was no way to add additional turns at different inclinations. Moreover, the object always had to be inside the framing field: had it been even a little larger, it would not have been possible to translate the object or the microscope reciprocally to achieve a parallel, as well as a convergent, overlap between several shots.

These examples found in the literature led us to a series of observations concerning the photogrammetric employment of USB microscope captures, noticing that the utilisation of specially designed components would be motivated by additional specific factors. Among the main reasons for the development of mounts to adapt USB microscopes for photogrammetric purposes are: limiting vibrations during shooting; ensuring sufficient framing for the overlap required to achieve a successful reconstruction despite the extremely narrow field of view; performing acquisitions while ensuring convergence of captures, i.e., management and control of the reciprocal positions of the optical system and the object; and the large number of shots to be taken in a short time.

Therefore, intending to keep costs down, this study proposes prototyping an initial low-cost, complete, and portable configuration based on the use of USB microscopes for image-based scanning, additionally verifying the possibility of gathering the different hardware components in one system.

2 Accessory Photogrammetric Component Design

To facilitate and speed up the acquisition process and to appropriately integrate USB digital microscopes into the photogrammetric workflow, an initial prototype was assembled for the systematisation of a real low-cost digitisation system based on the photogrammetric paradigm, i.e., the "3DINO SYSTEM". It consists of a series of mechanical supports whose frame is entirely 3D printed and supplemented with standard components readily available on the market. The design of the prototype is based on the idea of modularity, which allows the structure to be broken down into three main parts, properly connected and movable; they may also be used independently: the base (see Fig. 1 at numbers 1–5); the rib (7–10); the specimen holder (6).

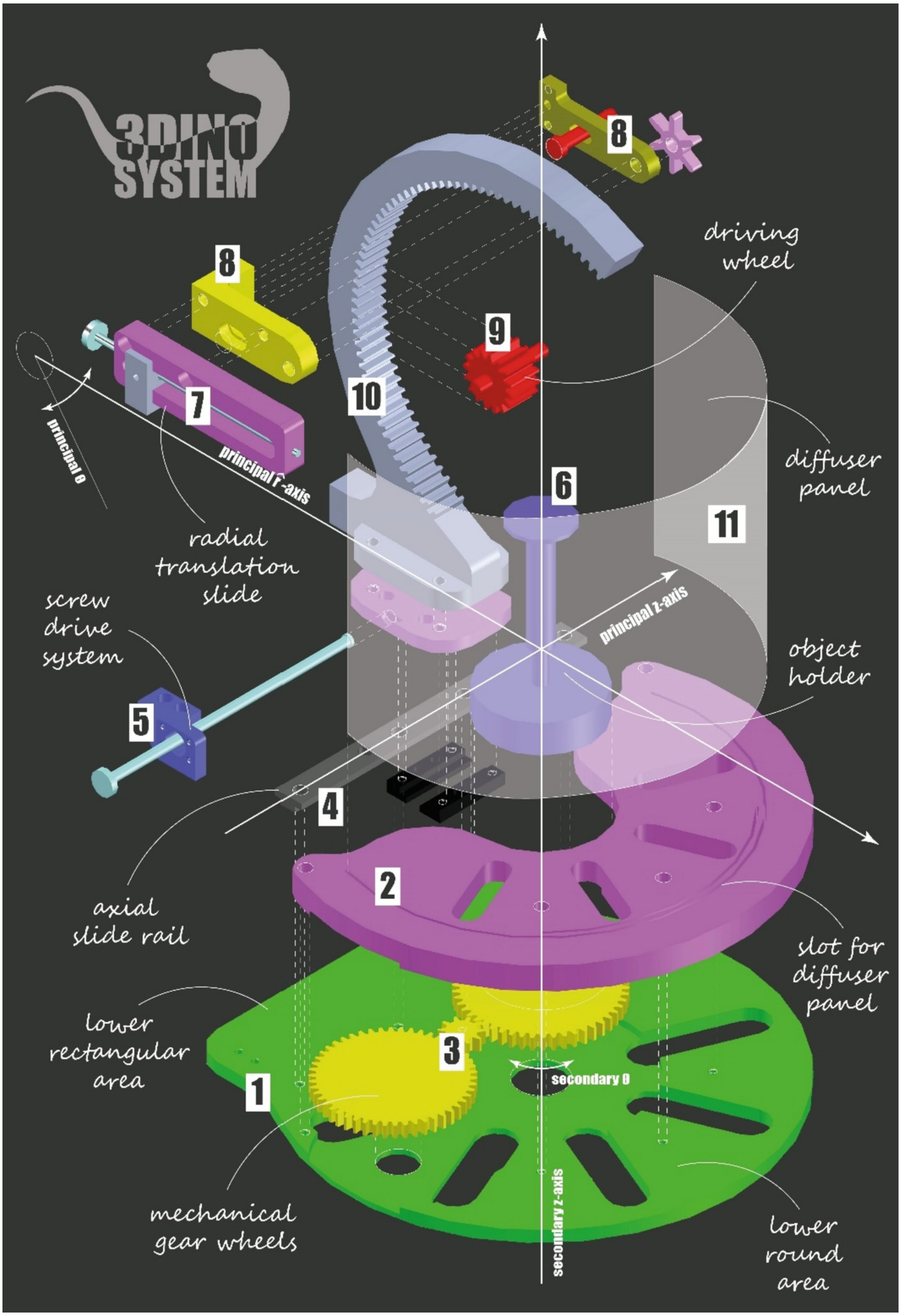

Fig. 1. Diagrams (exploded axonometric view) of the first prototype of the 3DINO SYSTEM based on the photogrammetric use of USB microscopes. The different parts, the base (numbers 1 to 5), the rib (7 to 10) and the holder (6), can be connected and moved independently.

These three controllers work together to obtain converging captures always orthogonal to the surface of the object, i.e., the axis of the camera is orthogonal to the plane tangent to the surface of the object in relation to the trace of the axis itself, which is the best condition from a photogrammetric point of view (see Fig. 2 and Fig. 3). Although the system was designed for small size photographic sensors, the modularity conception also makes it possible to utilise it in the case of photogrammetric sets for SLR cameras.

Regarding USB microscopes, due to their lightweight and small size, the entire optical system can be tilted against the object to be scanned. Tilts are ensured by the C-shaped rib, to which a micrometric slide is also fixed in order to accommodate the microscope, allowing it to move radially towards the centre of the system. Hence, we associate a "principal r-axis" with the radial movement of the optics, whose inclination – corresponding to the sensor's tilt – is referred to as an angle called the "θ-principal". Instead, the object is placed on a central support to be adjusted in height for the vertical alignment of the centre of the frame with respect to the object along the "secondary z-axis". Conversely, horizontal alignment is ensured by translating the optical system (rather than the object) along another axis defined as the "principal z-axis".

Thanks to a joint placed in the base, the tested specimen can also rotate 360 degrees around the "secondary z-axis" in increments of a specified "θ secondary" angle, enabling a complete revolution for each camera tilt.

The design of the individual areas of the 3DINO SYSTEM is thoroughly analysed as follows. The support base consists of two parts: a lower parallelepiped (see Fig. 1 at number 1, Fig. 2 and Fig. 3 referring to the green element), which houses a slide (4, in grey) constrained to slide along a guide in a longitudinal direction (according to the principal z-axis). The movement of the slide is via a mechanical gear (5, in purple and cyan) of the worm-worm type (also known as nut-worm). The transmission ratio of this type of gear is equal to:

$$\frac{2mm}{rotation} \Leftrightarrow \frac{2mm}{2\pi\, rad} \tag{1}$$

The nut of this gear is secured to the base using a screwed-on bracket; on the other hand, the worm gear is bound axially at the end of the slide, allowing the rotational freedom of the same screw to be maintained. The toothed rib is fixed on the slide via threads and constitutes the equipment's main part (10, in grey, described below). The base, consisting of two concentric parts (1 in green and 2 in pink), covers a circular area with a radius of 180 mm. In between, there is a technical compartment accommodating three toothed wheels (3, in yellow) with module 2 (the parameter on which the dimensioning of the gear is based, defined as the ratio between the primitive diameter[3] and the number of teeth of the wheel) with a transmission ratio (ratio between the two angular speeds) almost equal to one. The first (positioned in the centre of the system) and the third (projecting to the right) wheels, which allow for the rotation at the base of the central support (6, in purple), are partially visible. The tolerances of this gear are related to the accuracy of the 3D printing technology used during the prototyping phase (down to 0.2 mm).

[3] The diameter associated with the circumference along which the contact of the gear pair takes place, corresponding to the fictitious friction wheel capable of transmitting motion [21].

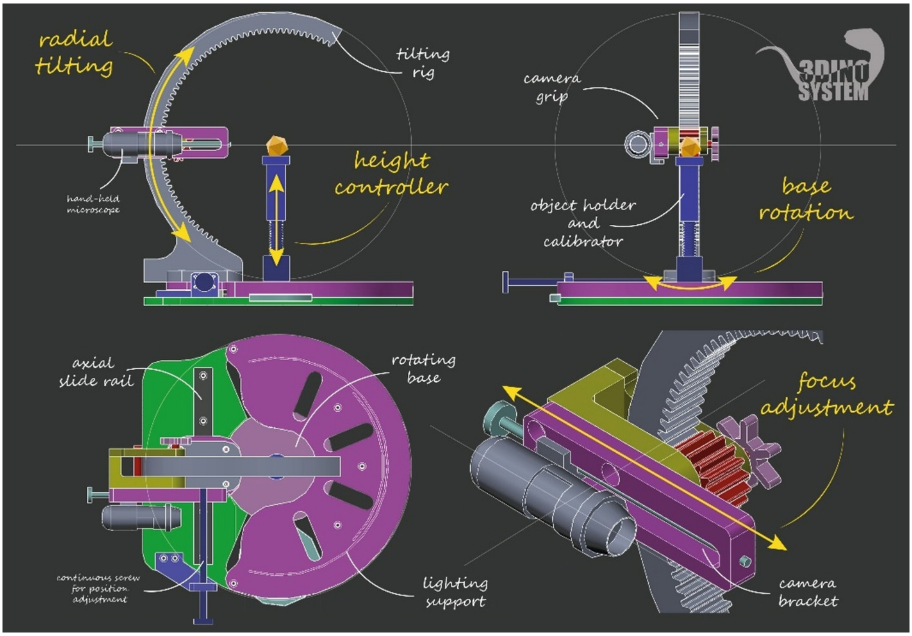

Fig. 2. Diagrams of the first prototype of the 3DINO SYSTEM: side and top views, axonometric detail (bottom right) of the optics housing structure.

As specified, the central wheel's rotation axis will be referred to as the secondary z-axis, and its rotation angle represents the secondary θ-coordinate. A support (6, in violet) can be attached at the centre of this wheel, with adjustable height (right along the secondary z-axis).

At the circular edge of the base, a small channel is envisaged for inserting a diffuser panel (11, in semi-transparent white).

The already mentioned rib is composed of a half-wheel with internal toothing having a primitive radius of 150 mm and a small, toothed drive wheel (9, in red) to which is connected a slide (7, in pink) suitable for the radial translation of the optics. To this radial translation, we associated the principal r-axis; instead, the angle that the optics slide forms with the horizon will represent the main θ-coordinate. The modulus of these gear wheels is similar to the previous one (equal to 2).

The equipment ultimately has three degrees of freedom for the optics and two degrees for the surveyed object. The principal θ-coordinate is related to the rotation of the small driving gear (9, in red), the pinion:

$$\theta = \frac{\textit{pinion radius}}{\textit{150 mm}} \cdot 2\pi \cdot (\textit{pinion's rotation}) \tag{2}$$

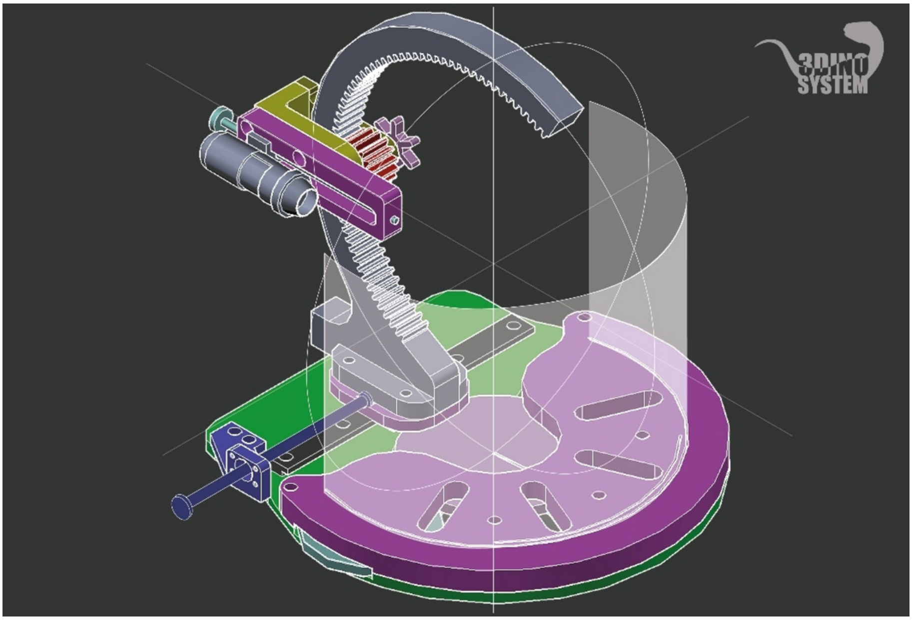

Fig. 3. Diagrams of the first prototype of the 3DINO SYSTEM: axonometry of assembled components with the addition of a diffuser panel for lighting.

The rationale underlying the sizing of the components is due to the constraints associated with performing movements compatible with the area framed by the microscope. Generally, the appropriate field of view for making acquisitions is an area of approximately 20 × 15 mm, which means moving the microscope and the object with millimetre precision. Furthermore, since the specimen housing area is designed as a detachable module, it must be large enough to accommodate up-to-15 cm objects for them to be acquired even with the sensor of a smartphone or, possibly, a conventional camera (dispensing with the utilisation of the rib).

3 Prototyping with Prusa I3 MK2.5S

The single parts were manufactured by FDM (Fused Deposition Modeling) technology using a Cartesian printer, the Prusa i3 MK2.5S [22].

In the additive manufacturing process, a three-dimensional object is produced by heating a thermoplastic filament to its melting point and then extruding it; layers of material are then deposited to shape the required components (see Fig. 4). It is worth noting that additional vertical support structures could be required for this type of 3D prototyping technique to sustain overhanging pieces during the printing process.

The filaments used are PLA (Polylactic Acid) for the auxiliary parts and ABS (Acrylonitrile Butadiene Styrene) for the structural-mechanical components, as they are subjected to higher stresses. PLA is a plastic of organic origin and is relatively affordable and easy to use in 3D printing. Although it comes with some disadvantages that limit its use, it is suitable for rapid prototyping. It combines high printing speed with sharp edges well, provided the material is properly cooled. It also benefits from a very good surface finish and low thermal expansion. In addition, the resulting parts tend to present very low deformability.

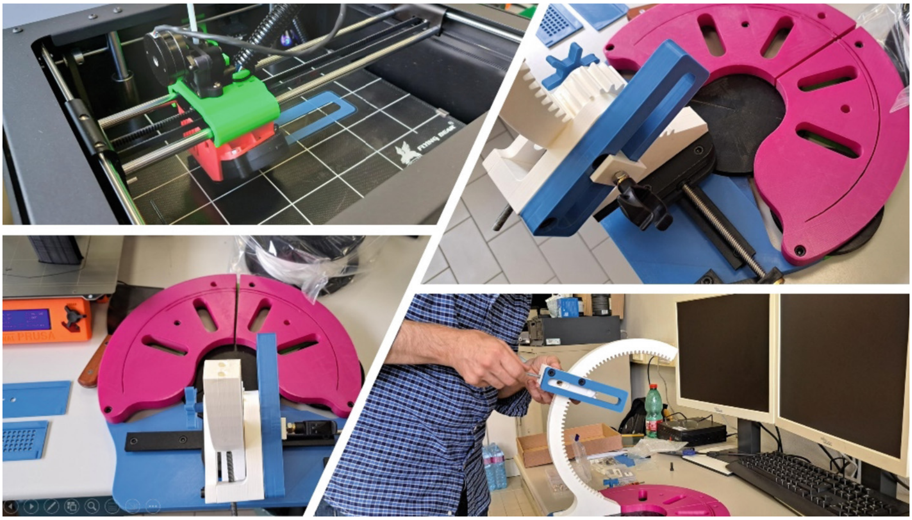

Fig. 4. 3DINO SYSTEM prototype manufacturing and assembling.

However, solid prototypes made from PLA are not designed to be subjected to mechanical stress, as the material is hard and brittle, nor to be exposed to intense heat sources (there would be a softening process over 60°C), and it does not withstand exposure to the atmospheric agents well.

Therefore, ABS – known for its toughness and impact resistance, producing durable components that can endure higher levels of use and wear – was used for the parts subjected to stress, even though it is harder to print. Indeed, ABS is a plastic material that shrinks in contact with air, often causing the 3D-printed elements to warp (or deform) and thus detach from the plate.

The diameter of the filaments, dictated by the printer's specifications, was 1.75 mm for both materials used. The printing specifications are listed as follows: extrusion (hot-end) temperature of 210°C and heat-bed temperature of 60°C for PLA and 100°C for ABS; layer height of 0.15 mm; 10% honeycomb pattern infill; the average print speed was equal to 60 mm/s. These values resulted in a total printing time of approximately 7 days (including finishing).

4 First Conclusions

Early uses of the prototype revealed some imperfections and limitations.

From the perspective of components production, the printer bed's size did not allow printing objects larger than 20 cm in diameter; this resulted in larger components being split into several pieces. Although these parts can be glued or otherwise fixed together at a later stage, this is never done precisely enough or even as accurately as if they had been printed in one piece. While this is considered to be acceptable in prototyping, it highlights the need for larger printing plates and even the possibility of excluding FDM 3D printing from final production. In addition, specifically for future prototyping, the deformation of the pieces should be taken into account; it is due to uneven temperature distribution within the printing chamber or between the areas of the piece directly in contact with the plate and those that are layering above it. Shrinkage of the material during cooling should also be managed by ensuring appropriate printing conditions, explicitly checking that the surrounding temperature is not too low: the faster the part is cooled, the greater the stress on the model. This is why working with closed printing chambers or at least ones sealed off from the environment would be advisable. Anyhow, in our case, the size of the elemental components and their orientation relative to the laying plate also played a disadvantageous role in terms of deformation, as large models are more susceptible to deformation.

To overcome many of the present issues, a new prototype is currently being developed that will be manufactured using selective laser sintering technology. This process, employing polymer powder, provides numerous improvements over FDM solutions. First of all, printing takes place in a controlled environment, thus overcoming the problem of deformations. The maximum size of the printable components is larger, allowing to reduce the number of joints between the sub-parts. Finally, the absence of supports will make it possible to redesign the axial slide rail and recess it inside the base itself, thereby giving the support greater stability. Conversely, it will most likely be necessary to perform a surface treatment on the new prototype, as the outputs of this technology are characterised by high porosity, which could adversely affect some elements' ability to slide over each other.

Another improvement will concern the weight of the base, which must be increased for higher durability of the system and vibration limitation. Indeed, despite the overall performance of the components being good, we are still far from ensuring sufficient vibration control. However, considering that the tested specimen rotates once the inclination of the chamber is fixed, this can be resolved by limiting the interaction between base and rib and rebalancing the components' weight.

Future developments will also include the general streamlining of the massive components, such as the fastening system for the micrometric slide of the optics to the rib. In addition, the movement of the rib, which is determined by a nut-screw mechanism that pushes the system along a T-shaped track, is sometimes tiring for the operator. Indeed, introducing a ball screw could increase precision, ease the operator's task and solve the asymmetry and instability caused by the overhang of the current screw. This would also allow the mechanism to be recessed into the base's thickness to lower the system's centre of gravity and hide the track.

Further adjustments could be implemented on the rib mechanism, which, although valid in its current state, would benefit from more precise axial tightening and a smoother sliding mechanism.

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