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Research

Reconfigurable and versatile augmented reality optical setup for tangible experimentations

Bruno Bousquet¹  · Martin Hachet² · Vincent Casamayou³ · Erwan Normand¹ · Jean-Paul Guillet⁴ · Lionel Canioni⁵

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Abstract

HOBIT, which stands for "Hybrid Optical Bench for Innovative Teaching and learning" is an educational platform that leverages the combination of numerical simulation and physical manipulation to facilitate learning of complex phenomena and motivate users about wave optics in practical work. HOBIT operates in real time and is self-adaptive, providing realistic displays of optical phenomena with virtual augmentations designed to facilitate their understanding. HOBIT makes it quick and easy to build any reconfigurable optical experiment. Students can manipulate optical components and observe the changes induced on detectors and displays. We detail the technology, the simulation model and the initial teaching aids. Current and future enhancements should meet the needs of students at different levels, from high school to higher education degrees.

Keywords Optics · Education · Tangible · Augmented reality

1 Introduction

Science education stands on numerous mathematical models and representations. This is particularly true in Physics and related fields, making the task of learning these abstract concepts difficult for many students [1]. Compared to purely theoretical approaches, lab work experiments that allow students to directly observe the results of their actions, offer clear advantages. Indeed, by physically manipulating the concept, students take an active role in the learning process, which has been shown as a key component for the understanding of complex and abstract phenomena [2, 3]. In Optics, for example, students can adjust mechanical stages holding the optical components, and observe or capture optical patterns and light-related quantities. Lab work experiments are thus essential and largely spread in many higher education curricula. However, despite their essential role in Optics teaching, current experimental setups suffer from limitations. The first one is that some abstract concepts related to optical phenomena are not directly visible. The optical wave frequency and the polarization of light, for instance, are often misunderstood by students [4]. The second limitation is that many optical setups are expensive and difficult to operate when they include high-precision mechanical stages or active components such as acousto-optic crystals, and so on. In addition, they may present maintenance and safety issues, especially when they are equipped with laser sources. To mitigate these problems, some of them are only accessible in

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preset fixed configurations. Hence, students cannot benefit from grounded cognition and active learning by manipulating freely the optical setup and investigating collaborative strategies, whereas both are essential for understanding complex phenomena and are highly encouraged [5]. Finally, classical optical systems often do not induce strong motivation, yet it is well-known that motivation leverages understanding and learning [6]. To overcome these limitations, virtual laboratories based on numerical simulations are often used in physics teaching [7, 8]. They offer flexibility and enable students to better understand simulated experiments [9]. PhET simulations, for example, have been widely developed over the years and are applied to various scientific disciplines [10, 11]. However, these simulations often rely on a 2D visualization of the experiment and do not allow the manipulation of physical objects, which, as previously mentioned, can be important for learning abstract phenomena. With the emerging use of immersive technologies, new types of digital simulations, such as tangible user interfaces (TUIs), virtual reality (VR) or augmented reality (AR), are being investigated to mitigate these problems [12–14]. For TUIs, a mixed reality installation using projection can augment a physical environment with digital educational information. As a result, students can still directly observe and manipulate physical phenomena in a real-world context, while gaining knowledge about the theoretical part of the experiment [15].

In order to explore and apply this concept to the teaching of optics, we have developed a platform called the Hybrid Optical Bench for Innovative Teaching and learning (HOBIT), which combines the advantages of a well-equipped optical setup with the benefits of digital simulation and augmented reality. HOBIT is the outcome of a design-based interdisciplinary research project made to answer the expectation of teachers at “Université de Bordeaux”. In contrast to a classical setup, HOBIT enables one to easily and quickly install and adjust many optical experiments, operate tunable optical components, avoid safety and maintenance issues, and finally create and test any open configuration from scratch on an active learning basis, with pedagogical support brought within the experimentation.

2 Method

2.1 General concept

Our basic motivation was to build a simulator able to perform a very large number of optical experiments in a very realistic way with extended pedagogical visualization supports. HOBIT is composed of a set of fake optomechanical mounts equipped with electronics that can be plugged onto the HOBIT breadboard (Fig. 1). The resulting network of connected mounts allows the direct control of a real-time digital simulation that propagates the light from a source to the next optomechanical component, and so on, until hitting either a detector or the visualization screen. It includes a large variety of light sources, optical components mounted on appropriate mechanical holders, detectors and accessories. Perfectly

Fig. 1 Photo of the HOBIT, which consists of a realistic optical table equipped with repositionable fake optomechanical components working as a real-time and self-adaptive setup. The calculated optical pattern is displayed on a vertical visualization screen, while pedagogical supports are projected on both the projection screen and the table itself, co-located with the related physical components



mimicking the real optomechanical components that can be found in an optics laboratory, HOBIT enables sensorimotor learning of technical gestures. In addition, beyond the basic result of the optical simulation, HOBIT projects data measured by detectors, feedback from the components and pedagogical helps that supports the understanding of complex optical phenomena. It also supports automation facilities, as well as signal recording and data extraction. Additionally, most of the optical characteristics of the components can be virtually modified to understand their influence and extend the use of HOBIT to unconventional situations.











The HOBIT concept was first presented in 2015 at the ETOP conference [16] and its first assessment for educational support was presented in 2017 at the CHI Conference on Human Factors in Computing Systems [17]. While the first version was a non-reconfigurable Michelson interferometer, the current one is fully reconfigurable and enables its user to build any optical experiment based on the available components. It calculates the properties of the light beam at the different locations gradually without a priori knowledge of the final experimental setup.

2.2 Hardware design and system description

The hardware of HOBIT consists of two types of devices, the first one is a specially designed optical table with instrumented connection holes to which the physical components are connected. The second type consists of table-top components that mimic real objects, such as light sources, optomechanical components, sensors, and accessories. The table exhibits a 2D grid of 34 holes/plugs for hosting the components. Each connection hole supplies power to the connected component and connects it to the digital network. A spacing of 12 cm between the holes has been chosen to reduce shadowing issues caused by the mounts while projecting rays and augmentations onto the table. Each node of the grid is labelled, and the exact position of each component is transmitted to the computer. In addition, each plugging stage on the table and each component are equipped with a magnetic encoder enabling to select the value of incidence angle from -90° to $+90^\circ$ by a 22.5° step and transmitting it to the microcontroller. This grid of nodes/plugs and incidence angles allows a realistic duplication of the optical experiment in a virtual model. Each component plugged onto the table, is described by both the characteristics of the optics itself, which are numerically set, and those of the hosting mechanical holder. We selected at this time five types of tunable mechanical components to fulfill the standard requirements of the usual optical setup. Components equipped with a single encoder/adjuster have been adapted to mimic an adjustable slot mount and translation stage, giving a standard resolution of $500\ \mu\text{m}$ per revolution which can be digitally modified to $50\ \mu\text{m}$ per revolution for fine-tuning. Moreover, the resolution can be numerically changed on-demand to examine the effect of much smaller variations. The second type of component mimics a steering mirror mount; it is equipped with two adjusters/encoders that yield $\pm 3^\circ$ of angular vertical and horizontal adjustments. This component can also hold a diffraction grating. The third one is equipped with three adjusters/encoders; it is used to mimic a gimbaled three-axis optic tilt mount. The fourth component, equipped with a rotation encoder, is used to mimic a rotation mount. All these adjusters/encoders-equipped components exhibit ergonomics and resolution similar to real ones. Finally, the last component equipped with an encoder, which is a rail for long-range positioning, is exclusively used to adjust the position of a lens to obtain a sharp image on the visualization screen or on a detector. Some other components mimic mounts that are not tunable via encoders (light sources, lenses, plates, and detectors). In addition, we have designed a transparent sensor that can be plugged into the table like any regular optical mount. It provides the user with all the physical parameters of the light beam passing through it, without disturbing the experiment. Up to now, it is implemented as a polarization sensor, but it could also be set to provide the phase and amplitude distribution in the transverse plane of the propagating light beam. Finally, the last component developed that can be plugged onto the HOBIT table has been called the universal driver. It has been designed to be numerically connected to different types of encoders present on the optomechanical components. It simulates the automated action of the targeted encoder at a selected speed. The counterpart of this universal driver is not a single equipment, but a series of motorized mechanical stages connected to their electronic drivers. This universal driver could also automatically tune a targeted parameter of any optical component, such as the blaze angle of a grating, the thickness or refractive index of a plate, etc. The list of optical components and mechanical holders available in the present version is given in Table 1.

The general schematic view of HOBIT is given in Fig. 2. In practice, each component plugged onto the table is equipped with a microcontroller that enables it to transmit—via a physical network located beneath the table—its full set of data to the computer. The transmission rate of the network (9600kb/s) with less than 10 bytes per sensor, allows an update in less than 10ms, that is faster than the refresh rate of the display and simulation. The data coming from the fake optomechanical components are sent to the simulation which generates in real-time a resulting image that is displayed on a $75 \times 45\ \text{cm}^2$ vertical screen by a first video projector (#6 in Fig. 2). This way, users can observe in real time how their

Table 1 List of the HOBIT optomechanical elements

				
a. Light source	b. Basic mount	c. 1-axis translation stage	d. 2-axis angular tilt mount	e. Gimbaled 3-axis angular tilt mount
				
f. Rotation mount	g. Adjustable slit mount	h. Long-range translation stage holding lens	i. transparent sensor	j. Universal driver

(a) Light source is numerically selected; (b) basic (not tunable via encoder) mount hold optics such as lenses, mirrors, plates, detectors, etc.; components equipped with one (c), two (d) and three (e) encoders; (f) rotation mount for polarizing optics; (g) one-encoder mount to tune the slit width; (h) converging lens moving on a rail equipped with an encoder; (i) the transparent sensor can be used to interrogate the polarization state and other characteristics of the electromagnetic wave; (j) the universal driver enables to automatically tune in a given range the targeted parameter of any component

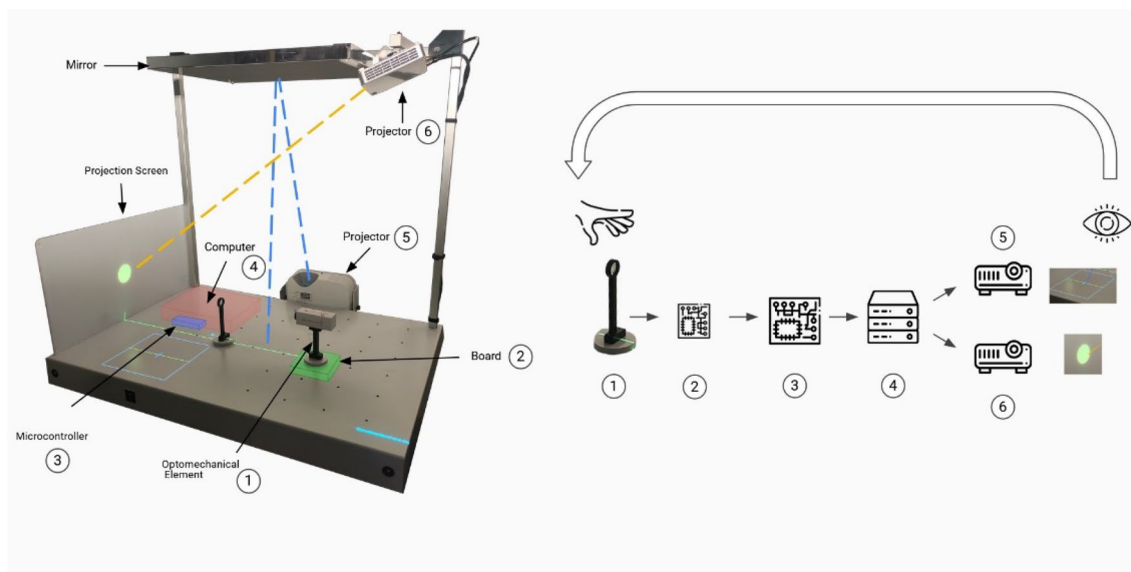


Fig. 2 General schematic view of HOBIT. The user manipulates an optomechanical mount (1) equipped with electronic sensors. Information is collected by an electronic board (2) and sent directly to the microcontroller (3), which communicates with the computer (4) to update the simulation. The resulting optical pattern and augmentations are displayed by the video projector (5) and (6) on the table, and the projection screen, respectively, providing feedback to the user

actions impact the optical response, as they would do with a real experiment. We use a second video projector (#5 in Fig. 2) to display the pedagogical support onto the $1.2 \times 0.8 \text{ m}^2$ table (see the section Augmentations). Technically, this projector, located at table level and pointing upwards, projects an image onto the table thanks to a $60 \times 40 \text{ cm}^2$ flat mirror located 1.8 m from the ground, avoiding the need to install the projector on top of a mast. Because we know the exact geometry of the physical table, we can display augmentations at precise locations, either close to the optical mounts or in selected areas.

Finally, the design of HOBIT makes that the light projected by the two video projectors is hardly occulted by the hands of the users manipulating the components and favors immersive user experience. The current resolution of the two video projectors is sufficient in most cases. However, anti-aliasing algorithm has been implemented in addition to super sampling to suppress Moiré patterns in case of small-size features. Moreover, digital transformations correct the distortions observed in the images due to out-of-axis projections. Obviously, good co-location between the components plugged onto the table and the virtual model is very important to propagate and deviate the light rays at the right places to provide a realistic display and a satisfying user experience.

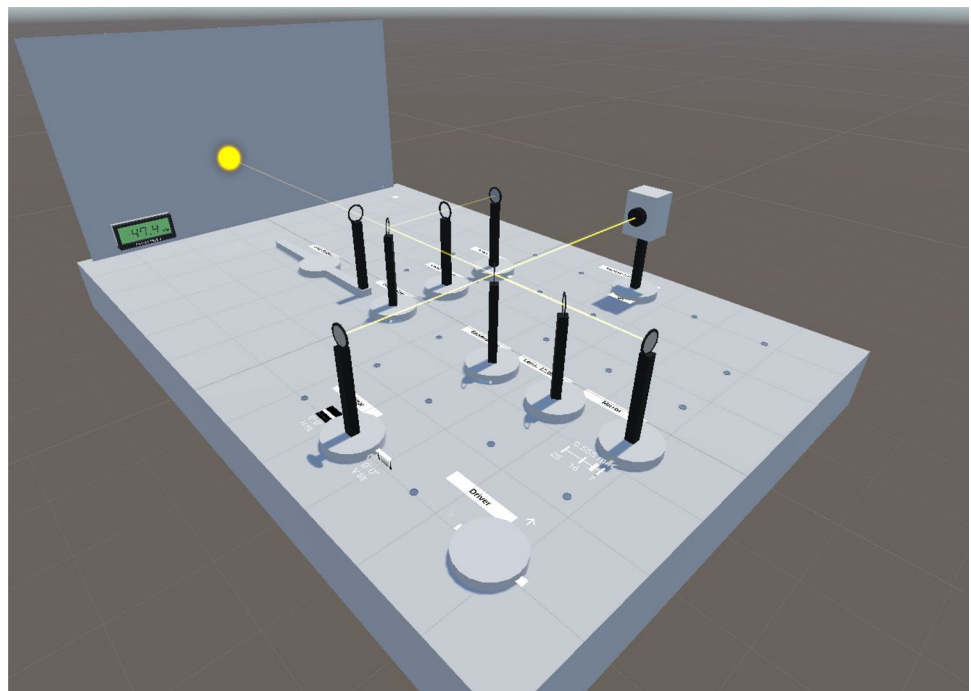
2.3 Software design and architecture description

The main requirement for HOBIT is its ability to be self-reconfigurable, the virtual model is self-constructed according to the components that are plugged onto the table and their settings. This strategy makes possible free manipulation thanks to graph chains and enables to run the optical model corresponding to the hardware while displaying relevant augmentations. In this section, we describe the software architecture (2.3.1), the optical model that calculates the properties of the propagating light waves (2.3.2), and the detectors management and their related measurements (2.3.3). Note that the method for designing and locating pedagogical augmentations will be presented in the separate section Augmentations.

2.3.1 Software architecture

The HOBIT platform relies on an interactive model (Fig. 3) that virtually reproduces what is happening on the optical table previously described. The shape and size of the table, as well as the location of the projection screen, are initially set on an underlying 3D geometric model that virtually replicates the physical table. Then, each optomechanical component plugged onto the table has its virtual counterpart present at a corresponding location in the virtual model. As soon as the status of an optical element is modified, it is sent to the simulation and finally, the updated optical pattern is projected

Fig. 3 Visualization of a 3D virtual scene extracted from the model of an experiment built from scratch



onto the physical platform together with data and augmentations, all in a seamless transition. The simulation is based on four steps updated at a rate of 60 frames per second.

Step 1. The data transmitted by the components are collected by the main micro-controller and transmitted to the computer where they are used to update the virtual model of the optical bench including all the components plugged onto the table.

Step 2. The collected data that include ray optics, wave optics, and electromagnetic optics, are sent to the optical simulation which calculates the output values.

Step 3. The pedagogical augmentations, which are updated according to the collected data and results of the simulation, are embedded in the virtual model.

Step 4. The projection step involves the use of two virtual cameras that capture the calculated optical pattern, the panels related to measurements, and the pedagogical augmentations, and send them to the video projectors.

The virtual model is implemented and managed by the 3D game engine Unity 2021.3.20f1, C# scripts, and HLSL shaders. The shaders require at least a DirectX 11 capable GPU. The current version of HOBIT software runs on a small desktop PC located inside the technical table with an Intel Core i5-7300HQ CPU (4 cores at 3.2 GHz), a NVIDIA GeForce GTX1060 GPU, 16 GB of RAM under Microsoft Windows 10 environment. We have chosen such performance to enable the PC to run the most complex calculation and displays during the phase of project development. However, the code related to the optical model is compact enough to be run on a standard PC hardware. Thus, we have successfully run our software on a NUC 6 with an Intel Core i3-6100U Processor CPU (4 cores at 2.30 GHz), an Intel HD Graphics 540 and 4 GB of RAM.

2.3.2 Optical simulation

The optical simulation is based on a model that stands on a multi-layer architecture. The first layer describes ray-optics and consists in ray transfer matrix analysis under the paraxial approximation. The second one describes wave optics and is based on the scalar wave theory in which light is described as a single scalar wave function. The third layer of our model describes electromagnetic optics, and includes the propagation of the electric field vector, related to light polarization. This layer naturally encompasses the one based on wave optics, which itself encompasses the one based on ray-optics. The model architecture allows future implementation of quantum optics as additional layer. This strategy makes the HOBIT concept relevant from high school to higher-education levels with adjusted pedagogical goals and levels of complexity. The challenge tackled by HOBIT is to provide real-time status of the physical parameters of the light beam from the source to the next component on its path, and so on, until the observation screen or a detector is hit. Thus, the architecture of our self-generating optical model is based on the following three steps.

Step 1. Starting from the light source, the chain of components playing a role in the light propagation is built. When the incident ray is split in two by a beamsplitter, the model considers the two branches. Note also that two light sources or more can be plugged simultaneously, generating as many chains as sources. The optical axis is optionally displayed all along the optical bench(es), enabling to visualize the active chain(s). This first stage of ray tracing, with refraction and reflection when the ray intersects an object, is directly implemented on the graphics card for greater fluidity.

Step 2. Beams propagation is calculated through the well-known ABCD matrix formalism that applies to both incoherent light source and Gaussian laser beam as the input variable [18]. In our model, we mix these two approaches by considering that any light beam can be described as a set of individual astigmatic Gaussian beams according to a preset spatial distribution. Both the spatial and temporal coherences of the beams are considered to describe a large variety of light sources. This original approach enables to approximate the high divergence and poor focusing of a white light source but also to model the existence of specific planes to observe interference patterns. Light propagation in the case of polychromatic source is modeled by simply calculating the chain of ABCD matrices for a series of selected wavelengths sampled in the source spectrum.

Step 3. Finally, polarization management induced by optical retardation components as well as reflectivity and transmission of optical components is integrated through the Jones formalism [19].

2.3.3 Detectors management and measurements

HOBIT includes a series of reconfigurable detectors. When a light wave reaches a detector, a calculation of physical quantities takes place at this specific location. In the current version, a single component can mimic a power meter, a CCD camera, or a photodiode by setting its type via a dialog box. Each type of detector opens a dedicated display panel in the vertical screen. These windows are located at specific locations on the screen, without overlapping, enabling to

exploit at the same time the different types of detectors on a same optical setup. When the detector is set to a power meter, HOBIT displays a panel showing the related measure screen with realistic appearance. The value displayed by this detector is refreshed at the rate of 60 frames/sec and is the integration of the intensity calculated over the whole light beam, assuming in the current version an infinite size for the sensor by default. Then, when it is set to a camera, the related panel is showing an image refreshed at the rate of 60 frames/sec. In the current version, both the size and sensitivity of the sensor are preset and not tunable by the user, as well as the number of pixels. Finally, when the detector is set to a photodiode, two hypotheses are made. The first one is that the active area of the photodiode is infinitely small so that the resulting signal is the intensity value at a single point located on the optical axis. The second one is that the photodiode is automatically connected to an oscilloscope. Thus, HOBIT displays a representation of this oscilloscope front panel on its vertical screen. The values of intensity are also refreshed at the rate of 60 frames/sec. In addition to the live mode set by default, when the record mode is selected, the oscilloscope is waiting for a trigger, like in real-life conditions, and can be synchronized with the universal driver. The signal recorded by the photodiode during the action of the driver on any targeted parameter is shown on the screen and automatically saved.

2.4 Augmentations

Beyond the satisfying optical simulation of light propagation through any arrangement of optomechanical components, HOBIT enables to display pedagogical supports on both the horizontal and vertical projection planes. These supports provide visual feedback of different kinds, namely optical axis, values of mechanical parameters that can be finely tuned via encoders, values of optical parameters that can be numerically set by the user, and pedagogical contents. They can be delivered under the teacher's control, on a case-to-case basis, depending on the selected pedagogical scenario, the student's expected background, and the level of autonomy targeted during the session. We have carefully selected both the contents and locations of the pedagogical supports as follows.

2.4.1 Optical axis/propagation

Starting from the light source, the optical axis is displayed in a horizontal plane located at a fixed height from the table in the 3D virtual model and projected onto the physical table. After hitting each new optical component, the emerging ray redefines the new optical axis, neglecting multiple reflection effects. After hitting a beamsplitter, the two emerging rays are displayed, illustrating the two paths that must be considered in light propagation. After hitting a diffraction grating, the resulting diffracted rays are displayed on limited distances to facilitate the understanding of this phenomenon and the observation of possible overlaps between diffraction orders in case of polychromatic light source. This augmentation can be optionally hidden.

2.4.2 Mechanical and optical parameters

At the base of each component, HOBIT displays its label (e.g. lens, mirror, polarizer, etc.), and the real-time updated values of the tunable parameters (e.g. position, angle, etc.). A button also displayed in the same zone of projection opens a dialog box (via a mouse click) presenting all the settings related to the component. For a glass plate for instance, the user can modify the thickness, and the material used. Only few conditions for optical components, considered as the most relevant ones, have been preset in our software but its architecture enables the increase of the number of items and/or values the user can select. This type of augmentation is strictly related to the components independently of the light propagation.

2.4.3 Pedagogical contents

Some graphical contents were designed to facilitate the understanding of abstract concepts and the link between optical patterns, measurements and manipulations/adjustments of the optomechanical components. They enable to "see" physical parameters that are not directly visible in real-life (e.g. polarization state, optical path difference, etc.) and that are usually only indirectly accessible after a significant effort of interpretation. In the current version, pedagogical contents are displayed at preset locations on both projection planes. On the vertical screen, at the right-hand side of the optical pattern, are displayed graphical contents related to interference, including the phase-shift, the total intensity at a preselected point of the pattern, and the optical path difference between the two interfering waves. This last information

is given for up to five values of wavelength sampled in the spectrum of the light source. On the top left-hand side of the optical pattern, is displayed a pedagogical content specially developed to show the light polarization state at the exact location where the transparent sensor configured as a polarization sensor is plugged. This graphical content, updated in real-time, shows on-demand 2D and 3D representations of the temporal evolution of the electric field vector, as well as orientation of the last polarizing component. When a photodiode is plugged onto the table, the corresponding oscilloscope panel, that is automatically displayed on the visualization screen, can be modified—via a simple click—to an augmented oscilloscope. In this case, the horizontal axis does not represent the elapsed time but the varying parameter, such as polarizer angle, mirror position along the optical axis, etc. Moreover, another type of pedagogical content is projected onto the horizontal table. It is a schematic top-view of a sub-area of the table, centered on the location of the component that can be accessed by a click on a dedicated sign. When asked from a beamsplitter, this content displays a zoom-in of this component represented as a thick plate, indicating on which side is deposited the chemical coating responsible for the reflection. Thanks to this help, the user can understand on which arm of an interferometer the compensator should be placed. When asked from a diffraction grating, this content displays not only the different diffraction orders at the right angles and with realistic colors, but also the blaze angle thanks to a representation of orientable microscopic surfaces. It thus enables to establish a link between macroscopic observations and microscopic properties.

3 Results and discussion

3.1 Setting up and controlling any optical bench

Thanks to its self-adaptive architecture and its specifically designed augmentations, HOBIT enables to build from scratch any optical bench as imagined by the user, and even different experiments at the same time. It can manage in real-time multi-actions on different components and allows synchronous collaborative work. HOBIT is not limited to a series of preset experiments but propagates light in any configuration. Once the components are installed onto the table, they can be repositioned and reoriented at any time with real-time feedback via updated display of the optical axis. HOBIT enables to modify their mechanical parameters either by acting manually on encoders or automatically by using the driver. It also enables to numerically modify the optical—and sometimes also the mechanical—characteristics of each component via a dialog box. For instance, the user can modify the focal length of a lens, the thickness, material properties, and reflectivity of a plate, the retardation of a retarder, the aperture of a slit, the blaze angle and the period of a diffraction grating, etc. Additionally, a same encoder can be numerically associated to different preset resolution values. For instance, one full turn on a screw-encoder can be assigned to either 500 or 50 μm , and even less if necessary. Another advantage of HOBIT is its large choice of light sources, including, in the current version, spectral lamps characterized by one to several emission lines such as thallium, sodium, and mercury lamps; halogen and LED white sources; and a selection of laser sources such as He–Ne, and Nd:YAG. Moreover, the optical power of each light source can be numerically modified to optimize the visualization, and/or detection of the optical patterns. The current version of HOBIT enables to observe on the visualization screen the optical pattern resulting from the selected imaging, and interference and/or polarization conditions. It also allows to install detectors at locations selected by the user on the optical path and thus visualize data that are updated in real-time. Users can also optionally record these data after automatic control of a targeted parameter. HOBIT exhibits a very high level of versatility and enables to fast and easily explore the influence of many parameters.

3.2 Getting help from pedagogical supports

The pedagogical supports provide precious help that facilitates the building, adjustments and operation of any optical setup, as well as the understanding of abstract concepts. We illustrate here the advantages of HOBIT through the presentation of three optical experiments, being the Michelson interferometer, a polarization bench, and a spectrometer.

After setting up a Michelson interferometer in less than one minute thanks to the augmentation projection of the optical axes onto the table (Fig. 4), a sharp image of the interference pattern can be easily obtained by moving the imaging lens through its long-range encoder and maximizing the image contrast. The graphical representation of the phase-shift at a given wavelength beside the interference pattern is very helpful for the basic understanding of constructive/destructive interference. It is also possible to correlate the fact that the interference pattern can become blurred for some values of the optical path difference (OPD) with the opposite variations of the intensities of a doublet of wavelengths, like those of the low-pressure sodium lamp. The graphical representation of OPD values in case of polychromatic light

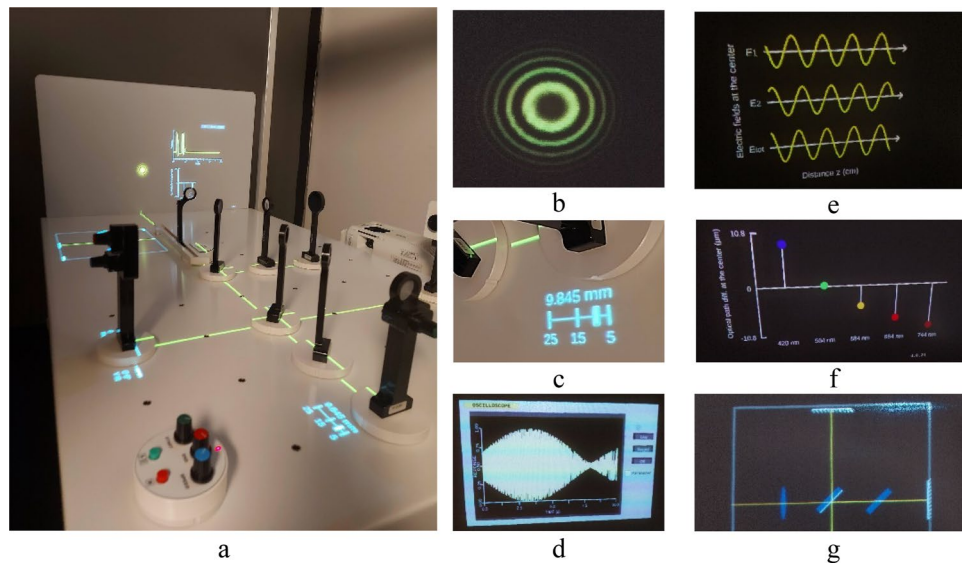


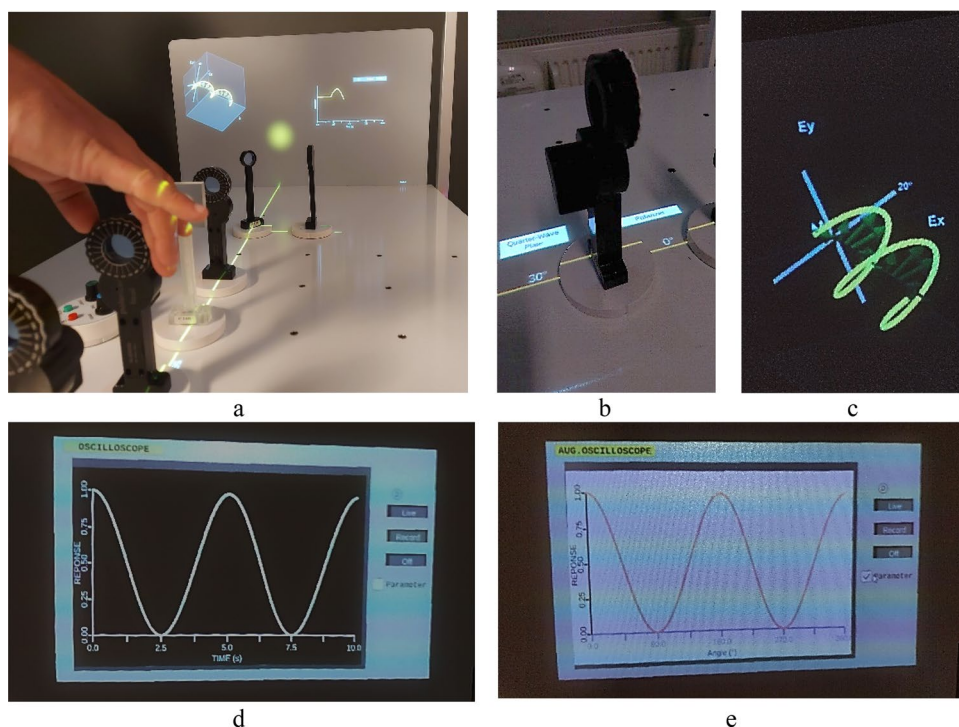
Fig. 4 **a** Michelson interferometer built from scratch on HOBIT, with automation and measurement equipment and teaching aids; **b** example of interference pattern displayed on the vertical viewing screen; **c** position of the moving mirror translation stage displayed on the table; **d** interferogram recorded by the photodiode during automatic translation stage movement; **e** phase shift between two monochromatic waves propagating in the interferometer; **f** optical path difference for five wavelength values for polychromatic light source; **g** top view of the beam splitter used to select the position of the compensator in the interferometer

source enables to check if the interferometer is balanced or not. Combined with the augmentations related to the beam splitter, namely the schematic top-view and the information about material and thickness, the OPD values enable the user to select the plate that perfectly balances the two arms of the interferometer. HOBIT permit not only to get trained to the basic manipulation of a Michelson interferometer, but also to examine extended experimental conditions. For instance, introducing a polarizer in each arm enables to modify the contrast of the interference pattern when acting on the two polarization directions. Moreover, it can be easily verified that it is not possible to balance the two arms of the interferometer at all wavelengths when two different materials, thicknesses, or orientations are selected for the beam splitter and the compensator. HOBIT enables to record interferograms with a photodiode digitally connected to the oscilloscope for different light sources and for different translation speeds for the moving mirror, as set on the universal driver. Here, switching from regular to augmented oscilloscope enables to display interferograms as a function of the mirror position, making it ready for use in future processing of Fourier transformation to retrieve the spectrum.

After setting up a bench of polarization with monochromatic light (Fig. 5), including polarizers and selected retarders such as half and quarter-wave plates, HOBIT enables to take advantage of the transparent (polarization) sensor specially designed to provide in real-time graphical display in 2D/3D of the light polarization state. The temporal evolution of the electric field is scaled down to the range of few Hertz to allow the user to observe it. HOBIT enables to rotate the different mounts holding the polarizing optics either manually, or automatically. The pedagogical support is displayed beside the beam spot on the visualization screen. It can be paired with the intensity signal displayed by the oscilloscope, and with all the values of orientation angles rendered onto the table. The combination of all these data and graphics provides a better understanding of the link between them. Starting with a pair of fixed and rotating polarizers, HOBIT makes it easy to understand the well-known Malus' law. In this case, the pedagogical support shows a sine function displayed in 3D in a plane that can be rotated by acting on the orientation of the last polarizer, and the photodiode records a signal for which minimum values are equal to zero when the two polarizers axes are orthogonal. Switching to an augmented oscilloscope provides this signal as a function of the rotation angle of the polarizer.

Then, when a retarder is introduced in the setup between the two polarizers and the transparent sensor—set as a polarization sensor—plugged just after it, HOBIT offers a unique opportunity to observe the polarization state at this location, which can be linear, circular or elliptic, simultaneously with the signal analyzed by the last rotating polarizer. Indeed, HOBIT significantly helps the interpretation of the detected signal, especially when it is displayed on the augmented oscilloscope panel. Thus, intensity minima—this time different from zero—are obtained when the rotating polarizer axis is aligned with the little axis of the elliptical polarization, as shown by the pedagogical support. Similarly, intensity maxima are recorded when it is aligned with the major axis. Moreover, HOBIT is perfect to understand that a

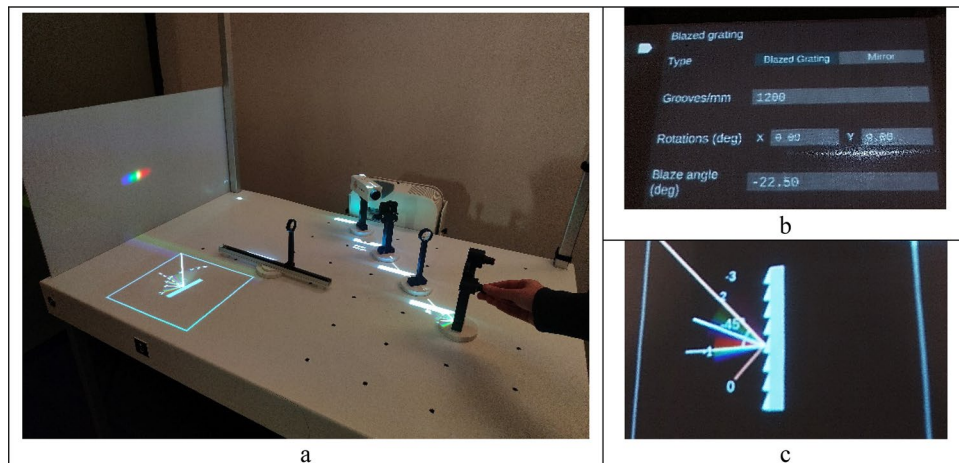
Fig. 5 **a** Polarization setup on HOBIT including polarizers and waveplate, as well as detector and viewing screen; **b** labels of polarizer and quarter-wave plate with their orientation angles in the laboratory reference frame; **c** the polarization sensor displays 2D/3D views of the polarization state (here elliptical) emerging from the quarter-wave plate oriented at 30°; **d** the oscilloscope displays an example of the signal recorded by a photodiode during automatic rotation of a polarizer in the case of linear polarization; **e** the augmented oscilloscope—activated by clicking on the *Parameter* button—now displays the angle values of the polarizer rotating on the horizontal axis, enabling the polarization state to be retrieved



residual signal modulation can be observed when a quarter-wave plate is oriented not exactly at 45° from an incident linear polarization. It also permits to examine the effect of a mismatch between zero-order or multiple-order waveplates, and the wavelength of the incident light.

After setting up a spectrometer based on a reflective grating (Fig. 6), the pedagogical support enables to see the different diffraction orders, from either monochromatic or polychromatic light sources. The superposition of microscopic and macroscopic information allows a schematic view of the blaze angle. HOBIT enables to monitor the light intensity at selected diffraction order and to numerically tune at the same time the value of the blaze angle. Thus, the best value for the blaze angle can be experimentally found through this measurement and justified through pedagogical support. Many tests can be achieved, by changing the number of grooves/mm, the incidence angle, and finally the blaze angle. After selecting a light source characterized by narrow emission lines, HOBIT also enables to easily observe the effect of the focal length of the converging lens used for the final imaging step on the spectral resolution. In the end, the focal length is set, as well as the characteristics of the blazed grating, and only the entrance slit width is tuned, exactly as in real life. The detector is set as a CCD camera and the image exhibits vertical lines with colors adapted to the discrete

Fig. 6 **a** Spectrometer on HOBIT made of adjustable slit, lens, steerable grating and on-screen imaging lens; **b** the dialog box opened by clicking on the settings icon of the grating allows the user to select the dispersion (number of grooves/mm), the fine tuning of the angle of incidence, and the blaze angle; **c** the top view of the grating shows the angular distribution of the diffraction orders and their relative intensity, as well as a schematic view of the blaze angle



wavelengths of the light source. Future developments will consist in achieving a pixel-to-wavelength calibration to obtain a ready-to-use spectrometer, and display on demand a spectrum instead of a 2D image.

4 Conclusion

Educational tools dedicated to Optics teaching were, until now, either real systems or simulators interfaced on computers. The first ones have the capability of training technical gestures but with limitation, safety, cost and maintenance issues. The second ones get rid of these disadvantages but prevent from learning real gestures related to building and adjusting optical setups. HOBIT being hybrid, it mimics a real setup and takes advantage of augmented reality, to offer a solution for innovative teaching with a safe operating system, allowing to learn technical gestures with a device identical to a real one and to better understand abstract physical phenomena as well as fine adjustments thanks to selected augmentations. This article describes the technology and the first intents of pedagogical help as the basement for further studies on educational sciences. HOBIT has already been used during lab works at the University of Bordeaux, France by several cohorts of 100 bachelor students and has been considered by students as a positive source of motivation and help for learning. It has been exploited in different ways. First, in the frame of demonstration made by the teachers, then as a self-learning platform for the students. In case of demo by the teacher, HOBIT provides safe, very fast and ready to use setup that increase motivation and satisfaction. Its versatility regarding light sources and optical components is ideal to show both standard and exotic showcases. When exploited as a self-learning platform, HOBIT can be used twice. Indeed, it can be operated to train to build and adjust real experimental setups, but also to verify the good understanding and know-how afterwards. In this last case, HOBIT looks like a serious game where the student must achieve tasks preliminarily defined by the teacher. Our own use of HOBIT encompasses both the demo and self-learning modalities. Moreover, our students are systematically exposed to real-life optical setups in addition to their training with HOBIT. We have observed a very satisfying transfer of know-how from HOBIT to real-life setups and also a deeper understanding of abstract physical concepts thanks to augmented reality providing simultaneous complementary information. Teachers and students at University of Bordeaux are now considering HOBIT as a real assistant increasing motivation and facilitating access to knowledge. Actually, students also use HOBIT to identify experimental biases that can occur on real-life experiments, so they can achieve self-correction of their work and thus valorize their autonomy. To date, six teachers have used HOBIT in practical work sessions during four years. Their feedback has been very positive, and we can mention some of the advantages they have noted: (i) the speed and ease with which the system can be set up, on the one hand, and the reproducibility of the optical phenomena observed and the measurements made, on the other, mean that the teacher can reduce set-up and restart times, leaving more time for teaching discussions; (ii) the diversity of the components makes it possible to exploit a very large number of situations and take advantage of their comparison to teach by example; (iii) the augmentations provide real-time access to physical information that is inaccessible on real systems, enabling the teacher to correlate observations/measurements with physical models/parameters, thus creating a new working environment spanning theoretical descriptions and experimental approaches. As far as feedback from students is concerned, HOBIT has clearly boosted not only their motivation, but also their sense of achievement and autonomy. They particularly appreciate the augmentations and the possibility of simultaneously tracking an optical figure on the projection screen, a signal measured by a sensor and the corresponding physical parameters. They also appreciated the trial-and-error approach, and were proud to have been able to progress through self-learning.

Both the hardware and software designs of HOBIT enable the community of users to build a large variety of reconfigurable optical setups on the table. The hardware part of HOBIT is now managed by a company that supplies the electro-mechanical table and associated components. The software part, which can run either on the table or on a separate PC/Windows environment, is destined to become an open software tool. It can be shared in its current version under specific conditions upon request to the authors. Future extensions of HOBIT may advantageously include additional capabilities such as nonlinear optics and laser physics, as well as active components such as acousto-optic and electro-optic devices, and more. Present augmentations are expected to match the needs of students at different levels from high school to higher-educational degrees and we are now considering the need for improving them or adding other ones. Moreover, we plan to test various pedagogical scenarios, with selected levels of help depending on the students' degree. And we also consider to include into HOBIT a series of preset challenges and answers in order to extend its ability to behave as a self-learning platform. One other future development aims at making HOBIT self-growing based on the principle that a given arrangement of optomechanical components can be shrunk into a new component to take part in future experiments. The components contained in a spectrometer are an excellent illustration of this idea. Thus, the new component

“spectrometer” will exhibit the characteristics defined at the time it was created. Of course, many spectrometers of different characteristics could be built. Similarly, it could be possible to create a new component “Fourier-transform spectrometer” from a Michelson interferometer, and so on. This strategy enables to building future optical setups much bigger than the size of the HOBIT table and/or involving several components much larger than the ones available in the basic version of the system. This future flexibility of HOBIT should also open the way to new strategies of collaborative learning. One team of students could be asked to develop a first stage of a future setup, then a second team, a second stage, either at the same time or not, etc. Each team could make and deliver its new component/stage. The assembly of all of them in a single final setup could highlight the key points of such a collaborative work. Finally, the concept of HOBIT may be easily transposed to acoustics and any other topics supported by physical models based on the same architecture.

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Declarations

Competing interests The authors have no relevant financial or non-financial interests to disclose.

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