Infrared vision of artworks based on web cameras: a cross-disciplinary laboratory of optics

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Abstract. Applied optics offers a way to teach fundamental concepts of light properties and radiation-matter interaction through interdisciplinary experimental activities. In this framework, we designed a cross-disciplinary laboratorial activity on optics applied to artworks based on DIY instrumentation for the secondary school level. The teaching sequence includes inquiry-based seminars and laboratorial activities on imaging, spectrometry, infrared applications to conservation science.

1. Introduction
Recently, Modern Physics has become part of the curriculum of secondary school in Italy. To this respect, applied optics offers a way to teach fundamental concepts of light properties and radiation-matter interaction through interdisciplinary experimental activities [1,2]. Moreover, a number of optical experiments may be designed using Do-It-Yourself (DIY) [3,1] materials, including sources, lenses, and web camera equipped with CCD-technology sensor.

Aim of this work is to propose a teaching sequence that is innovative in terms of a) physical contents, b) proposed laboratorial activities, and c) modern interdisciplinary applications. We construct and demonstrate the potentialities of a laboratorial learning sequence that integrates fundamental concepts of optics with non-destructive optical diagnostic techniques for Cultural Heritage. Our proposal addresses and puts together some of the main relevant topics whose value is highlighted by international literature: Inquiry Based Learning [4], Predict-Observe-Explain [5], Learning by Doing, Information and Communication Technologies, importance of transversal and interdisciplinary activities [6-7], bridge towards human science [8], advanced arguments of Modern Physics, Physics Education at University level, motivation in studying Physics [9].

The expected learning outcomes consist in a deeper understanding of physical concepts regarding optics and electromagnetic waves, fostered by a charming, practical and stimulant approach.

The formative module was developed by the laboratory OpDATECH (Optical Devices and Advanced Techniques for Cultural Heritage) of the University of Verona in the framework of the “Progetto Lauree Scientifiche”, promoted by the Italian Ministry of Education, University and Research. The course is proposed to 25 students from fourth and fifth year of two Scientific High Schools of Verona.

2. Description of the teaching proposal
The total duration of the activity is of 18 hours in six lessons, each one including a theoretical part (1h) followed by an inquiry-based practical laboratory (2h). The first two lessons concern physical and geometrical optics, imaging and spectroscopy in general, the third lesson is conceived as a seminar on applications to Cultural Heritage, the last three lessons constitute a sub-laboratory on infrared vision with theoretical and practical activities. All the theoretical parts are carried out in an interdisciplinary learning context, in which two different kind of professionals are involved: a physicist and a conservation scientist. Students, divided in groups of five, are requested to design and to assemble optical instrumentation, to predict the outcomes of simple experiments and then to compare the actual results with their previsions, in the aim to explain observed phenomena, according to the POE strategy [10]. Students were given practical goals to be achieved, in the form of problem solving: they are helped, when needed, or advised, but not guided step-by-step. In this framework, the role of teachers is mainly that of a guide, a counsellor and a facilitator [11], and his action is limited to supervision and assistance in the interpretation and assimilation of results. In this work, pre-tests are conceived and utilized as stimulus questionnaires to carry out the activities in an Inquiry Based modality.

The first theoretical lesson starts with an introduction, carried out by the conservation scientist, on the field of Cultural Heritage conservation and the so called noninvasive diagnostics, underlying the role of the non-contac te optical techniques in the study of artworks with the aim of introducing the concept of the use of the electromagnetic radiation as a probe. Canvas and panel paintings are choosen as application examples as the 2D flat object is suitable for the next introduction of imaging concepts.

The second part of the theoretical lesson, carried out by the physics teacher, focuses on light, and on electromagnetic radiation in general, and on geometrical optics. Reflection and refraction are recalled, and the ray-optics approximation highlighted.

In the laboratory session, the students work with optics educational kits (the Basic Kroncke Optical System by 3B Scientific) approaching experiments on formation of images in the visible range, verifying by themselves the thin lens formula, which was mentioned but not explained in detail in the lesson. The experiments are carried out in a traditional way using optical components (halogen lamp, set of lenses, targets, screen) mounted on rail carriers free to move on a linear guide rail. To conclude the laboratory session, a parallelism between the optical setups and the human eye is introduced. As a homework, the students have to reflect on the peculiar characteristic of the human being to perceive colours.

The second theoretical lesson first analyses the concept of colour perception and colour synthesis from the artistic and from the scientific point of view by presenting notable examples in which colour theories are applied to historical studies. The human vision is examined in depth, in particular the link between the physical phenomena and the physiological processes behind colour vision [12].

The second part on physics is focused on the concepts of light decomposition and spectrometry.

In the laboratory session, by exploiting the optics experiment kits and low-cost DIY instrumentation, the students are asked to build an optical spectrometer, and to use it for investigate the emission spectra of different sources. The diffraction grating is made by the small pits arranged in a spiral on the surface of the polycarbonate layer of a CD-ROM, exploiting it both as a reflective and as a transmission grating. The sources investigated are: a halogen lamp, an incandescent light bulb, a white led, a coloured led, and a laser pointer.

Last step is to show the reflectance spectra by introducing a commercial visible spectrometer (by Ocean Optics), which is used to measure the spectra of the sources (emission modality) and the spectra of different colour targets (reflectance modality). The bridge with art diagnostics is that the analysis is useful for pigments discrimination on real artworks, because similar pigments may have different reflectance spectra, and is made to guide the students towards the concept of spectrum as material response and of electromagnetic radiation as a probe.
In the first and the second lesson the students are asked to individually fill in a pre-test on geometrical optics (lenses and mirrors) and on colour perception and synthesis. No previous knowledge is required, and the tests are not exams graded by the teachers. The tests are useful to introduce new topics and to encourage the students to conduct a scientific reasoning by their own about topics they don’t know.

The third lesson is designed as a seminar on application case studies with the aim to provide an overview of the potentialities of the optical methods. Various diagnostics techniques are presented, based on multimodal imaging and spectroscopy in different bands, showing the connection between the physical phenomena concerning radiation-matter interaction and conservation.

The last three lessons constitute the single sub-laboratory specifically dedicated to the infrared vision of artworks.

The theoretical part of the lessons introduces the concepts of infrared radiation and its interaction with the painting layers, focusing on the concepts of scattering, of optical transparency of the pigment layers, and of image intensity contrast between the underdrawing and the preparatory ground. The experimental setup for infrared reflectography is illustrated: it is composed by two radiation sources, the artwork and the acquisition device. In this technique, the artwork is irradiated in the infrared and the backscattered diffuse signal is acquired as image (figure 1); briefly, as the pictorial layers are transparent to the infrared wavelength, the features underlying the visible surface that are hidden to the naked eye (i.e. in the visible range), e.g. the drawings and overpaintings, can be detected in the infrared [13]. The difference between wideband and multispectral modality is explained to build a bridge between the spectrometry and imaging modalities that guides the students to fix the underlying physical concepts. The technique of false-colour processing in the visible-infrared, largely used in the cultural heritage is explained (figure 2). The intention is to make the students approach the concepts of “viewing intensity” and “viewing frequency”. Finally, to underline the potentialities of the infrared reflectography technique applied for the study of artworks, some real case studies are shown.

The idea of the laboratory session is to design the infrared reflectography technique following a POE learning strategy and working in a DIY modality by modifying a web camera sensor [14]: the setup is re-invented in a didactical perspective, allowing the students to implement it by themselves.
The students are first asked to fill in a pre-test with questions about the components of the infrared reflectography setup, mainly concerning the source and the filter of the camera, applying the knowledge and the concepts previously acquired. The answers are then discussed and compared all together, followed by an experimental verification when necessary.

To perform an infrared reflectography study, a set of halogen lamps is used as a source and a high-pass filter is placed on the camera to block the visible spectrum and to record only the information of the infrared band. The spectrum of the source and the transmission spectrum of the filter are analysed with the spectrometer, verifying that they are suitable for the experiment.

As infrared pass filtering and visible blocking, the magnetically coated round plastic medium of a floppy disk is employed. To build a DIY infrared camera, the students replace the native cut-off infrared filter of the webcam with the infrared pass window, thus obtaining an infrared CCD (figure 3). The artworks to analyse are prepared by the students as 2D multi-layer targets using low-cost material. Different media, dry or liquid, trace the underdrawing on a white cardboard (the support), and one or more overlapping painting layers of different materials (coloured chalks, watercolours, and oil and acrylic paint in tubes) are spread on the preparatory drawing, covering it.

The students are finally asked to carry out the infrared experiment, working autonomously (figure 4). They are free to build their self-made setup with the material at their disposal (webcams, sources, targets), in order to collect two overlapping images, one in the visible and one in the infrared range. As last step they process the images in order to build up infrared false colour representations using GIMP, an open-source image editing software (figure 5).

Figure 3. Pictures from the laboratory session. The students implement the DIY infrared webcam in three steps: (a) open the web camera and remove the cut-off infrared filter from the sensor; (b) prepare a high-pass filter using an old floppy disk; (c) position the filter in front of the sensor to obtain an infrared CCD.
Figure 4. Pictures from the laboratory session. The students prepare the multi-layer targets and perform the infrared reflectography experiment with the infrared webcam.

Figure 5. Webcam images acquired in the visible and in the infrared band, and result of the False Color processing.

The conclusive step of the laboratory session is dedicated to the comparison of the work of the different groups and to the scientific presentation of results, which is essential in every research program. The scheme of a scientific paper is presented, explaining the different sections, and emphasizing the bibliographical approach as the starting point of every scientific investigation. To this aim, the students are introduced to the web search engine Google Scholar to collect bibliographical sources.

3. Discussion

The practical and operationally oriented setting of the proposed learning path proved to be effective, especially because students are directly involved in each step of the research. The laboratory activities are carried out autonomously and without specific guidelines previously given by the teachers. The students are always encouraged to collaborate and exchange the collected data and the personal observations, as the members of a real research team do.

In each lesson, the topics are briefly explained and then examined in depth during the practical work, in which the students are asked to reach a final goal. Thus, the inquiry-based learning approach is followed, instead of the traditional didactic method that goes from theory to practice. This methodology results to be stimulating, increasing their curiosity and engaging their active participation. As a result, the students gain a deeper understanding and a stronger knowledge of the physical phenomena involved.

For example, the work with the didactic optics kits helped the students to clarify the relationship between the focal length of a thin lens, the distance of the object and the distance of the focal point. They verified the thin lens formula both in a practical way and by mathematical proof. In particular, two peculiar cases have been considered and tested by the students: the first one concerns the rays that enter
parallel to the axis of the lens and converge to the focal point on the other side; the second one concerns the divergent rays from focal point that focus to infinity.

When called to assemble the optical instrumentation, the students have the chance to focus on the single components and to understand their function and application. As example, when building the spectrometer, the dependency of the optical resolution to the slit size is clarified: if the slit width is larger, the signal strength of the lines is higher, but the resolution decreases, resulting in overlapping lines.

When involved in practical activities, the interest and the curiosity arisen may lead the students to find creative solutions to achieve better results, as well as to investigate by themselves new aspects of the physical processes involved. For instance, during the spectrometry experiment the students created a lampshade to decrease intensity of the source. Moreover, even if without a specific request by the teachers, they tested some filters, understanding how they work. They set a blue and a yellow filter between the source and the grating, expecting to see a green line, but observing that any resulting line appeared on the screen. They explained the phenomenon suggesting that the blue filter only transmits light in the blue range, blocking the radiation with higher wavelength, including green and yellow, and that, on the other hand, the yellow filter blocks shorter wavelength radiation, including blue and green. This digression resulted to be extremely effective when the theory of optical filters has been explained in lesson four, as the students already understood their functioning.

During the sub-laboratory on the infrared reflectography, the POE methodology is appropriate to reach the didactic goal of the research. The pre-test form, with questions about the setup, encourages the students to show their initial ideas and hypotheses about the physical processes at the basis of the infrared reflectography technique. The following general debate, in which the students are asked to explain their answers, motivates them to investigate and to verify their predictions. The practical activity, in which they are called to assemble the instrumentation and the mock-ups, and to build up their own setup, and to carry out the experiment, helps to understand how the infrared reflectography technique works. The observations are discussed together, resulting in a final report, written as a scientific paper, in which the students have the chance to organize their ideas logically, to think clearly and to draw their personal conclusions.

4. Final remarks and conclusions

In the framework of the teaching of Modern Physics to secondary school students in Italy, we have designed an original cross-disciplinary formative intervention connecting optics and spectrometry to cultural heritage applications through hands-on activities and POE methodology.

Although a detailed analysis of the learning outcomes is outside the objectives of this paper, we can say that the proposed laboratorial sequence fosters students’ attitude towards learning physics, since it proposes a highly situated learning context, based on real-life tasks, whose efficacy is well known in the literature [15-16]. This feature, in turns, makes it possible to introduce at a high school level advanced physics topics usually hard to treat, such as: the nature of colour between perceptual and physical aspects, the quantitative characterization of colours (colorimetry) and the imaging in spectral ranges other than the visible band. As a matter of fact, the proposed formative module can also be successfully adapted to courses at the University level.

5. References

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