Digital video analysis of falling objects in air and liquid using Tracker
(*Análise digital de vídeos de objetos em queda no ar em líquidos usando Tracker*)

C. Sirisathitkul[1], P. Glawtanong[1,2], T. Eadkong[1], Y. Sirisathitkul[3]

[1]*School of Science, Walailak University, Nakhon Si Thammarat, Thailand*
[2]*Petcharik Demonstration School, Nakhon Si Thammarat, Thailand*
[3]*School of Informatics, Walailak University, Nakhon Si Thammarat, Thailand*

Motions of falling objects through air and liquid media were captured by a conventional digital camera and analyzed by a video analysis open source called Tracker. The position of the moving objects at every 33 ms was evaluated from series of images and the velocity was averaged from the change in position during each interval. For the falling in air experiment, the displacement of a ball was proportional to the time squared and the agreement with the theory was indicated by the derivation of the acceleration due to the gravity with an acceptable level of accuracy. In additions, the effects of the height of falling, the camera distance as well as the color of ball and background were investigated. In the case of falling in glycerol, the average velocity of a metal bead was initially increased with the time of falling until reaching a constant value of the terminal velocity.
Keywords: digital camera, video analysis, falling, drag force, Tracker.

Movimentos de queda de objetos no em meios líquidos foram registrados por uma câmera digital convencional e analisados por um software aberto chamado Tracker. A posição dos objetos em movimento a cada 33 ms foi registrada a partir de uma série de imagens, e a velocidade média foi calculada a partir da mudança de posição durante cada intervalo. Na experiência de queda no ar, verificou-se que o deslocamento era proporcional ao quadrado do tempo, confirmando-se a teoria pelo valor da aceleração da gravidade, obtido com nível aceitável de precisão. Além disso, foram investigados os efeitos da altura de queda, da distância da câmara, bem como a cor da bola e o meio ambiente. No caso de queda em glicerol, a velocidade média de uma bolinha de metal foi aumentou inicialmente com o tempo de queda até atingir o valor constante da velocidade terminal.
Palavras-chave: câmara digital, análise de vídeo, força de arrasto, Tracker.

1. Introduction

Digital video analysis becomes increasing influential in physics education because the visual display can make traditional lessons more intriguing and accessible for students [1,2]. Physics learning by digital video analysis has therefore been continuously improved in terms of hardware, software as well as contents. Page *et al.* suggested that high precision measurements can be achieved by the video analysis when possible sources of errors from projections, lens distortion and marker positions were controlled [3]. Furthermore, the data may automatically be acquired by incorporating the image recognition or computer vision [4-6]. Stereoscopic filming was also demonstrated to obtain 3-D data [7,8].

From video files recorded by either conventional digital cameras or webcams, the motion of an object can be analyzed. To this end, commercial software packages such as Vernier's Logger Pro and CMA's Coach have been developed and Tracker by Open Source Physics is available as freeware [9,10]. These software packages can be employed in the teaching of fundamental mechanics by visualizing the motion and analyzing the position of objects. The time-dependent position then leads to average velocity and acceleration. The lessons were extended to some intermediate concepts in physics including centrifugal force [11] rigid body [12,13] and damping [14]. Furthermore, some movements in sports were successfully analyzed in order to enhance the appeal of physics learning. For example, Cross explained the behavior of bouncing tennis ball [15]. Heck and Ellermeijer used Coach to analyze the sprinting of runners [16] whereas Chanpichai and Wattanakasiwich employed Tracker to analyze the throwing of basketball [17].

Falling objects in air and liquid are familiar case studies in high school physics. Still, new analytical and experimental techniques have been proposed to enhance

---

[1]E-mail: chitnarong.siri@gmail.com.

the understanding of these concepts [18-21]. In this work, we use a set-up composed of a digital camera and Tracker to identify the position of falling objects and analyze the variations in their position. To examine the accuracy of the set-up, the acceleration due to the gravity and the terminal velocity in the liquid medium are evaluated.

2. Experimental

Motions of manually released objects were captured by a digital camera (Sony DSC-W350, 14.1 megapixels, 720 p fine) in a video mode. From jpeg files of 30 sequential images per second (96 dpi) in a computer, the movement of the ball was followed frame by frame for a time interval 33 ms using Tracker 3.1. Positions of the middle pixel of the object in each frame were identified by the marker in the program and its coordinates were recorded as a function of time of falling. The error can occur due to the marker position. Besides, the center of the object may not coincide with individual pixel but fall between pixels. The uncertainty in the marking and locating the center of the object depends largely on the appearance of the moving object but should be kept within 2 pixels. Before recording each experiment, the image plane was carefully arranged to be parallel to the plane of motion in order to minimize systematic errors from the projection. In addition to the distances between a camera and the plane of motion, the height of the wall was also measured to relate to the length scale in the images.

For the falling in air experiment, the experiments were performed with different heights (1.0 and 3.4 m) and camera distances (2.0-16.0 m) exemplified in Fig. 1 as well as varying contrast between the ball and the background. For the experiment with liquid medium, a metal bead was dropped in the semi-transparent acrylic tube filled with glycerol. To reduce random errors, measurements were repeated and average values were reported.

3. Results and discussion

In Tracker, the position of the ball in each frame was identified and its displacement at every 33 ms (x) was shown as a function of time of falling. In Fig. 2, the plots of x against time squared (t^2) from 12 data points for 5 repeated drops from 1.0 m are compared to the theory. The theoretical line is plotted by the model builder in Tracker using an equation for the free fall
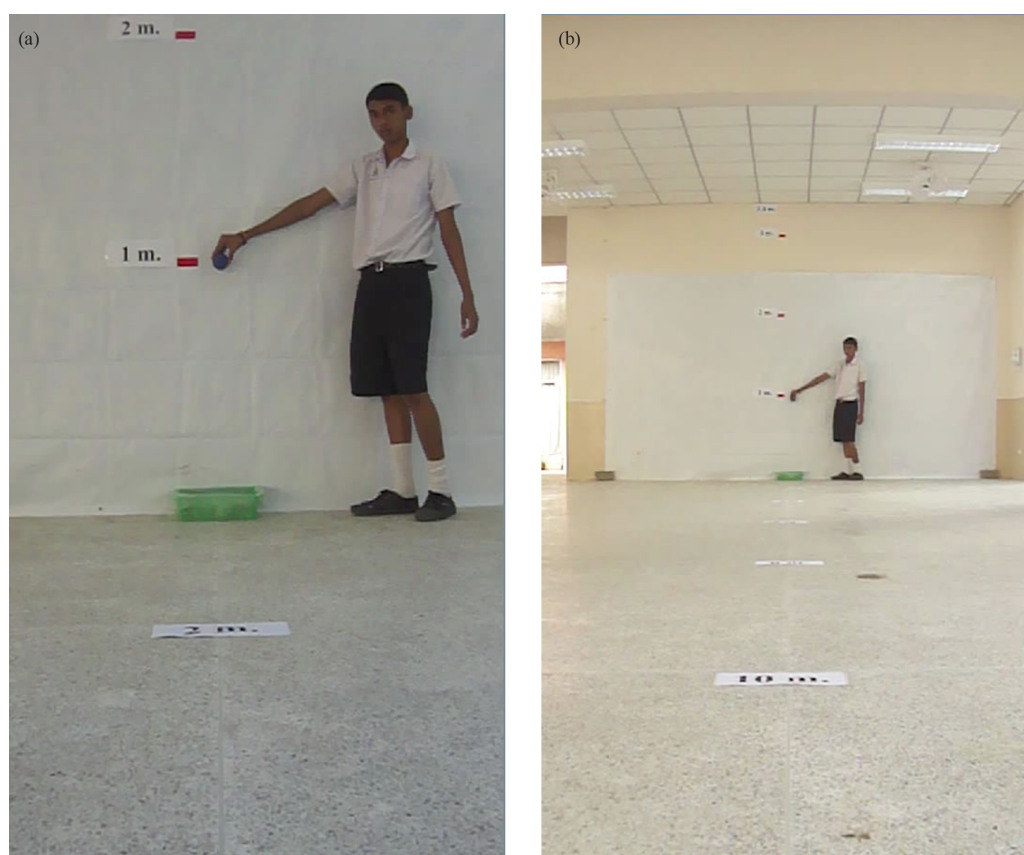
$$x = v_0 t + \frac{1}{2} g t^2, \tag{1}$$

Figure 1 - Examples of the falling in air experiments using a blue ball from 1.0 m with the camera distance of (a) 4.0 m and (b) 12.0 m.

where the acceleration due to the gravity (g) measured at the nearby Songkhla province by the National Institute of Metrology (Thailand) is 9.78120 m·s^{-2} [22]. All experiments give rise to straight lines with the interception near the origin indicating a negligible initial velocity (v_0) by the manual release. In Fig. 2, the obtained g value with the highest accuracy is 9.80 m/s^2 which differs from the standard by only 0.15 %. However, the average g value from all repeated experiments shown in Fig. 2 is 10.06 m/s^2. Any deviation from 1-D translation by random 'sideways' motion is inspected by drawing a vertical line in the program and it ranges from less than 10° to more than 10°. However, this deviation and the effect of drag force imposed by air cannot be accounted for the loss of accuracy because both factors tend to reduce the g value from the standard.
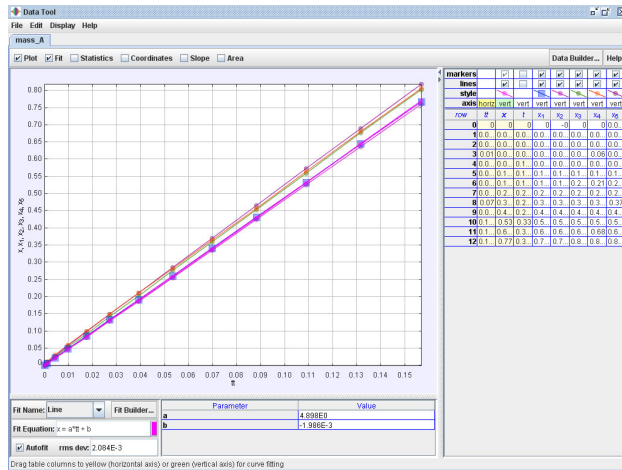

Figure 2 - The plot of x against t^2 from 5 repeated falling in air experiments compared to the theoretical line (the bottom line) from the model builder in Tracker.

To investigate other sources of errors, the height of the release and the camera distance were varied. Overall, the g value obtained from experiments with each camera distance in Fig. 3 is slightly lower when the ball was dropped from the height of 3.4 m than that from 1.0 m. This an indication of the effect of the drag force on the objects with high velocity. To a greater extent, the variation in the distance between the camera and the plane of motion affects the errors in g value from experiments. According to Fig. 3, the errors in tracking of falling objects from the height of 1.0 and 3.4 m can be reduced by selecting the camera distance from 8.0 to 12.0 m. This optimum range corresponds to the maximum clarity and the minimum distortion. Nevertheless, large errors in both shorter (2.0-6.0 m) and longer (14.0-16.0 m) camera distance in Fig. 3 are apparently random in nature and tend to average out resulting in comparable g values from repeated experiments.
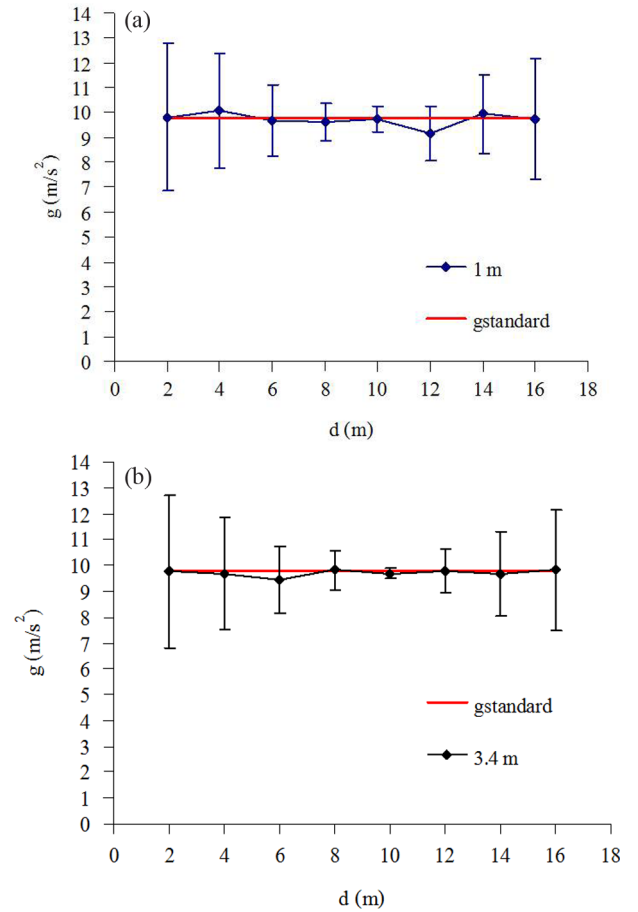

Figure 3 - The variation of g value obtained from x and t^2 graphs with the camera distance (d = 2.0-16.0 m) when a ball was released from the height of (a) 1.0 m and (b) 3.4 m.

In Fig. 4, the effect of the ball color with the white background is demonstrated. By choosing an orange ball, 19 points in the falling from the height of 2.2 m can be tracked. The numbers of tracked points in the case of blue and green balls are respectively reduced to 18 and 15 as the effect of blurry images of fast objects on the white background becomes significant. It follows that the g value with the highest accuracy is obtained when the orange ball is used whereas the green ball leads to the highest deviation from the standard. The experiment was also performed with different background colors along the height of 3.4 m as illustrated in Fig. 5. The sequential frames were then divided into 3 sets (frames 1-8, frames 8-16, frames 16-24) and analyzed from 5 repeated measurements. The average g value derived from the initial frames (yellow background) has the largest deviation from the standard (11.76%). The deviation is reduced to 4.28% in the case of the intermediate frames (yellow-white background) and the terminal frames (white background), by far, possess the minimum deviation in the g value (1.47%). The results clearly indicate that the error from the blurry images of fast objects up to 8 m/s is insubstantial. By contrast, the major source of errors is the low color contrast between the moving object and the background.
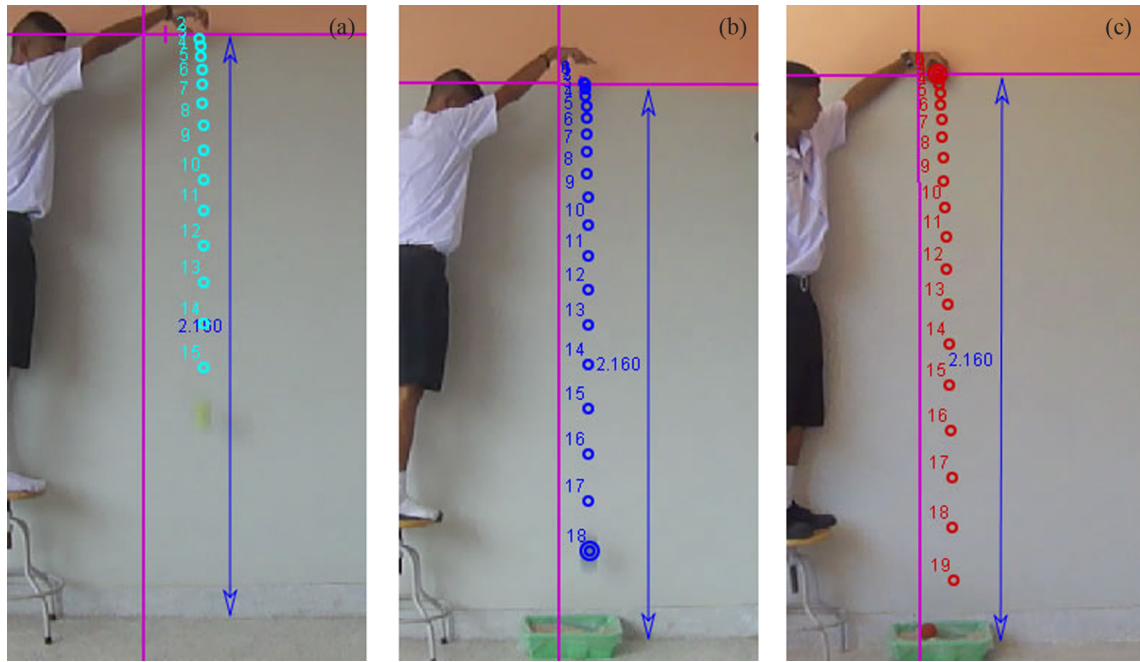
Figure 4 - Visual displays of the falling in air experiments with different colors of balls; (a) green, (b) blue and (c) orange. The number of tracked points is shown in each case.
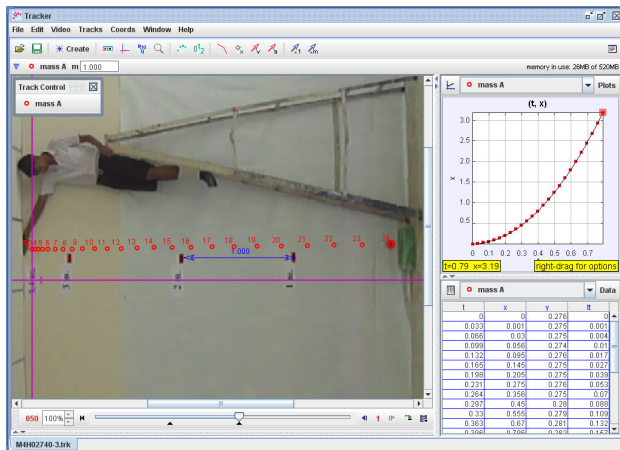

Figure 5 - The falling process after releasing a ball from the height of 3.4 m divided into 3 sets of frames on different background color.

Tracker can be used to follow the ball further after reaching the ground. The visual display and the displacement of the bouncing ball as a function time in motion are shown in Fig. 6. In addition to the vertical displacement (y), the ball exhibits significant horizontal displacement (x) and the motion becomes 2-D transition. The velocity in the vertical direction was averaged over each 33 ms interval and plotted as a function of time in motion in Fig. 7. In the first stage, the magnitude of velocity is increased until the ball bounces at the ground. By virtue of the impulse process, the velocity suddenly changes its direction with the loss some

magnitude. The velocity is further reduced as the ball travels upwards, then approaches zero as it reaches the maximum height before gaining the velocity with a subsequent fall. At each stage, the average velocity (v) has a linear variation with the time according to the fundamental formula
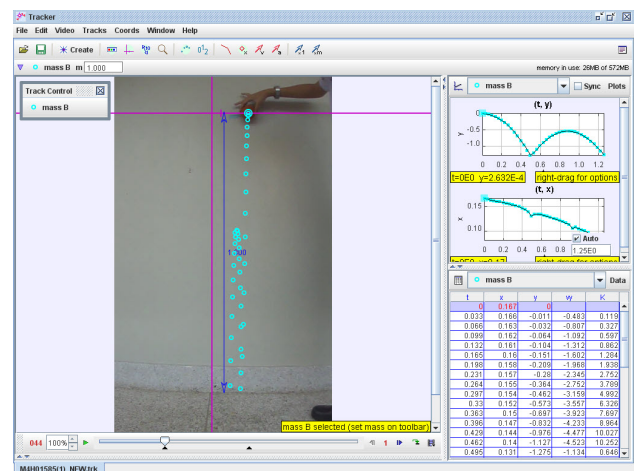
$$v = v_0 + gt. \tag{2}$$

Figure 6 - Visual display of falling and bouncing processes of a ball released from the height of 1.0 m. Variations of (x, y) coordinates with time in motion are also shown.

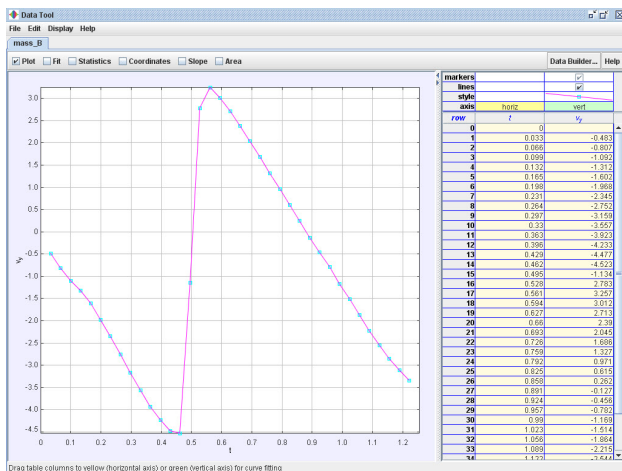Figure 7 - Variation of average velocity (v_y) with time in motion of the bouncing ball after the release from the height of 1.0 m.

Figure 8 - Visual display of a ball after directly throwing in the air. A variation of vertical displacement (y) is also shown.

In additions, the velocity of the upward and downward motions can be compared when the ball is directly thrown in the air as illustrated in Fig. 8. Although each pair of frames is captured at a slightly different height, the magnitudes of the velocity of upward and downward motions are comparable. At each height and velocity, the potential and kinetic energy at any instance can be plotted in Fig. 9 showing the conversion between these quantities. A constant summation of the potential and kinetic energy corresponds to the conservation of energy under the gravitational force.

By analyzing the series of images of the metal bead falling through glycerol, the displacement in Fig. 10 exhibits a linear variation with the time. The different characteristic from that of falling in air is attributable to the drag force imposed by viscous liquid (F_d). The average velocity in Fig. 11 exhibits an increase in magnitude of the velocity at the initial stage of falling. This corresponds to the gravitational force (mg) larger than the combination of the drag force and the buoyancy (F_b). As the velocity increases, so does the drag force in Stoke's law until the gravitational force is balanced by the drag force and the buoyancy. In such circumstance, the equation can be written as

$$F_d + F_b = mg. \tag{3}$$

Consequently, the velocity reaches a constant value of the terminal velocity as evidenced in Fig. 11. Errors at the end of the plot stem from a combination of a low clarity of the tube and a distortion of the small object at the edge of the image.
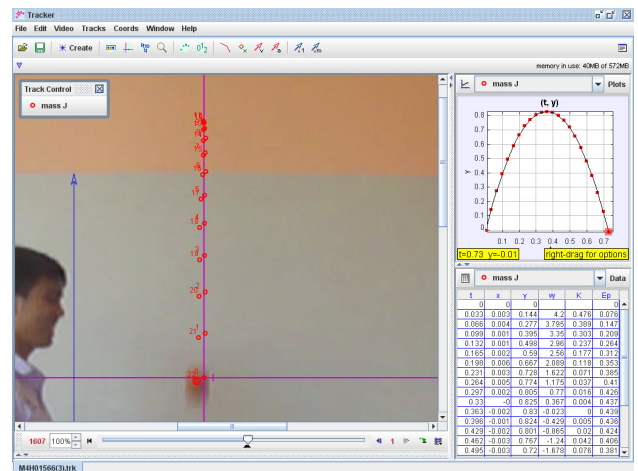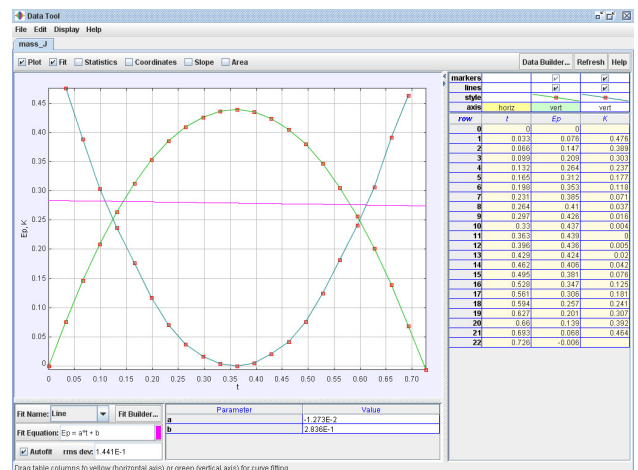
Figure 9 - Plots of potential energy (E_p, circular marker) and kinetic energy (K, square marker) against time in motion of the ball directly thrown in the air.
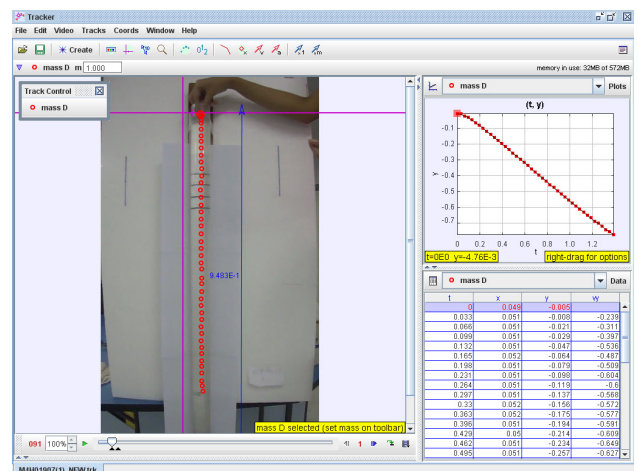
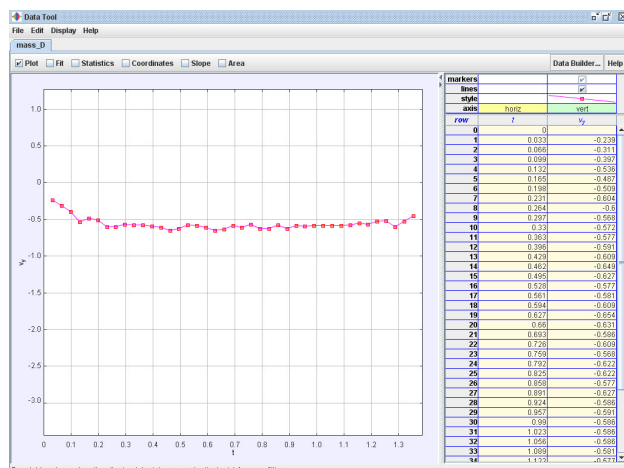Figure 10 - Visual display of a metal bead falling in glycerol and the plot of its displacement against time.

Figure 11 - Variation of average velocity (v_y) of the metal bead with the time of falling in glycerol.

4. Conclusions

The simple set-up consisting of a digital camera and video analysis open source, Tracker, was used to analyze the motion of falling objects. Experimental results were then compared with fundamental equations in mechanics to verify the technique. In the case of falling in air, the motion can be approximated as free fall and the g value of high accuracy was obtained. Moreover, the average velocity derived from digital analysis can adequately represent the instantaneous velocity of the thrown and bouncing balls. However, the accuracy of the experiment was severely affected by the camera distance and the contrast between ball and background. In the case of falling in glycerol, the results are compatible to Stokes's law and the evolution of average velocity until reaching the terminal velocity was displayed.

5. Acknowledgements

References

[1] R.J. Beichner, Am. J. Phys. **64**, 1272 (1996).

[2] P. Laws and H. Pfister, Phys. Tech. **36**, 282 (1998).

[3] A. Page, R. Moreno, P. Candelas and F. Belmar, Eur. J. Phys. **29**, 857 (2008).

[4] J. Riera, J.A. Monsoriu, M.H. Gimenez, J.L. Hueso and J.R. Torregrosa, Am. J. Phys. **71**, 1075 (2003).

[5] J.A. Monsoriu, M.H. Gimenez, J. Riera and A. Vidaurre, Eur. J. Phys. **26**, 1149 (2005).

[6] R.A. Bach and K.W. Trantham, Am. J. Phys. **75**, 48 (2007).

[7] E. Parrilla, J. Riera, J.R. Torregrosa and J.L. Hueso, Mat. Comput. Model. **50**, 823 (2009).

[8] J. Riera, E. Parrilla and J.L. Hueso, Eur. J. Phys. **32**, 235 (2011).

[9] Tracker: Video Analysis and Modeling Tool, `http://www.cabrillo.edu/~dbrown/tracker/`, accessed 15/9/2010.

[10] D. Brown and A.J. Cox, Phys. Tech. **47**, 145 (2009).

[11] A. Wagner, S. Altherr, B. Eckert and H.J. Jodl, Eur. J. Phys. **27**, L27 (2006).

[12] W.M. Wehrbein. Am. J. Phys. **69**, 818 (2001).

[13] S. Phommarach and P. Wattanakasiwich. in: Proceeding of the Siam Physics Congress 2011, Pattaya, Thailand, 2011, p. 322.

[14] C. Kaewsutthi and P. Wattanakasiwich, in: Proceeding of the Siam Physics Congress 2011, Pattaya, Thailand, 2011, p. 324.

[15] R. Cross, Am. J. Phys. **70**, 482 (2002).

[16] A. Heck and T. Ellermeijer, Am. J. Phys. **77**, 1028 (2009).

[17] N. Chanpichai and P. Wattanakasiwich, Thai. J. Phys. **5**, 358 (2010).

[18] E.P. Moraes Corveloni, E.S. Gomes, A.R. Sampaio, A.F. Mendes, V.L.L. Costa and R. Viscovini, Revista Brasileira de Ensino Física **31**, 3504 (2009).

[19] D. Amrani, P. Paradis and M. Beaudin, Rev. Mex. Fis. E. **54**, 59 (2008).

[20] K. Takahashi and D. Thompson, Am. J. Phys. **67**, 709 (1999).

[21] J.C. Leme, C. Moura and C. Costa, Phys. Tech. **47**, 531 (2009).

[22] Thailand Absolute Gravity Measurement Project, `http://www.nimt.or.th/nimt/include/g.html`, accessed 17/3/2011.