

## TABLE OF CONTENTS

<b>COVER</b>	<b>ii</b>
<b>ANTIPLAGIARISM STATEMENT</b>	<b>iii</b>
<b>APPROVAL FORM</b>	<b>iii</b>
<b>DEDICATION</b>	<b>iv</b>
<b>PREFACE</b>	<b>v</b>
<b>TABLE OF CONTENTS</b>	<b>vii</b>
<b>LIST OF TABLES</b>	<b>xi</b>
<b>LIST OF FIGURES</b>	<b>xii</b>
<b>NOMENCLATURE</b>	<b>xviii</b>
<b>INTISARI</b>	<b>xxi</b>
<b>ABSTRACT</b>	<b>xxii</b>
<b>I. INTRODUCTION</b>	<b>1</b>
I.1. Background . . . . .	1
I.2. Problem Statement . . . . .	6
I.3. Scope . . . . .	7
I.4. Goals . . . . .	9
I.5. Benefits . . . . .	9
<b>II. LITERATURE REVIEW</b>	<b>10</b>



II.1.	The Acoustics of Clipped Strings in <i>Bundengan</i> . . . . .	10
II.2.	Finger-String Dynamics in Plucked Instruments . . . . .	14
II.3.	Stereoscopic Methods for 3-D Measurement . . . . .	17
II.4.	Research Contribution . . . . .	20
<b>III.</b>	<b>THEORETICAL BASIS</b>	<b>21</b>
III.1.	The Motion of the String . . . . .	21
III.1.1.	The Wave Equation . . . . .	21
III.1.2.	Travelling Waves . . . . .	22
III.1.3.	Reflection and Transmission . . . . .	23
III.1.4.	Plucked String . . . . .	27
III.2.	Shadows . . . . .	30
III.3.	Image Formation in Camera . . . . .	32
III.3.1.	Mathematical Model of Pinhole Camera . . . . .	34
III.4.	Lines and Planes in 3-D . . . . .	36
III.4.1.	Equation of Lines . . . . .	36
III.4.2.	Equation of Planes . . . . .	37
III.4.3.	Line-Plane Intersection . . . . .	38
III.5.	Sensitivity of Measurement System . . . . .	41
<b>IV.</b>	<b>RESEARCH METHODOLOGY</b>	<b>42</b>
IV.1.	Research Procedures . . . . .	42
IV.2.	Literature Study . . . . .	42
IV.3.	Design the Measurement Setup . . . . .	42
IV.4.	Find Optimum Setup . . . . .	44
IV.5.	Modelling the Optical System . . . . .	44
IV.5.1.	Draw the Diagram of the Optical System . . . . .	44



IV.5.2. Derive the Equations of the Optical System . . . . .	45
IV.6. Sensitivity Analysis . . . . .	46
IV.7. Draw Conclusion . . . . .	46
<b>V. RESULTS AND DISCUSSION</b>	<b>47</b>
V.1. <i>Bundengan</i> String Plucking Motion Measurement Setup . . . . .	47
V.1.1. The Design of the Measurement Setup . . . . .	49
V.1.2. The Light Sources . . . . .	51
V.1.3. The Height Adjustable Sonometer . . . . .	53
V.1.4. The Screen . . . . .	55
V.1.5. The layout . . . . .	56
V.2. Mathematical Model of Measurement System . . . . .	59
V.2.1. The Intersection of Rays of Light and the Planes . . . . .	61
V.2.2. Mathematical Model of Fingertip Motion Measurement Setup	64
V.2.3. Mathematical Model of String Motion Measurement Setup . .	66
V.3. Sensitivity Analysis of Measurement System . . . . .	67
V.3.1. Sensitivity Analysis of Fingertip Motion Measurement Setup .	70
V.3.2. Sensitivity Analysis of String Motion Measurement Setup . .	76
V.4. Optimum Setup to Gain High Sensitivities . . . . .	81
<b>VI. CONCLUSIONS AND SUGGESTIONS</b>	<b>83</b>
VI.1. Conclusions . . . . .	83
VI.2. Suggestions . . . . .	84
<b>BIBLIOGRAPHY</b>	<b>86</b>
<b>APPENDICES</b>	
<b>A. LED Driver</b>	<b>92</b>



<b>B. Adjustable Table</b>	<b>96</b>
<b>C. Source Code</b>	<b>100</b>



## LIST OF TABLES

Table 2.1.	Comparisons table of stereoscopic measurement methods. . . .	19
Table 5.1.	The layout parameters. . . . .	58
Table 5.2.	The plotting parameters of fingertip motion measurement setup. . . .	68
Table 5.3.	The plotting parameters of string motion measurement setup. . . .	79
Table 5.4.	The summary of actions and consequences. . . . .	82
Table A.1.	LED driver's bill of materials. . . . .	95
Table B.1.	Table's bill of materials. . . . .	97
Table B.2.	Locking knob's bill of materials. . . . .	99



## LIST OF FIGURES

Figure 1.1.	The <i>bundengan</i> [3]. The shield-like shape (a) is <i>kowangan</i> , initially used as a protection for the duck herders from an unfriendly climate. To play this instrument, the right hand pluck the clipped string (b) imitating <i>gamelan</i> while the left hand pluck the bamboo plates (c) imitating <i>kendang</i> . . . . .	1
Figure 1.2.	The string vibration setup is a modified sonometer; it excluded the resonator to fit the simulation [8]. The main components are (a) the guitar tuner, (b) the wooden bridges, (c) the string, and (d) the spring scale. The bridges can be moved to adjust the string length. . . . .	7
Figure 2.1.	Parikesit and Kusumaningtyas shift the bamboo clip position toward the centre of the string (Pos 1 to Pos 5). Consequently, in (a) the first and second frequency shift to a lower frequency, while the third and fourth frequency shift to a higher frequency. From left to right; (b) shows the spectrogram of Pos 1 to Pos 5. Attack transient is pre-eminent in timbre recognition [23], (b) shows that transient vibration in <i>bundengan</i> is mostly composed of high frequencies. . . . .	11
Figure 2.2.	Picture frames from the high-speed video recording [5]. The bamboo clip is more massive than the string; it resembles a fixed end. From frame one to eight, we barely see it moves transversally. The plucked part (longer string) moves earlier than the unplucked. The unplucked start to moves in frame four with lower frequency. . . . .	12



Figure 2.3.	A perfect triangular shape string emerges more high harmonic frequencies resulting in a brighter sound [20]. . . . .	14
Figure 2.4.	Pavlidou's finger model [21]. The finger assumed to be two-dimensional, moving in a plane perpendicular to the string length. The flesh of the fingertip is not modelled. The muscle-spring compress and expand; it provides forces to the finger. . . . .	15
Figure 2.5.	(a) A mirror and a high-speed camera are used to measure the three-dimensional position of finger-string. (b) the direct-view captures movement in the XY plane, and the mirror-view captures the ZY plane. (c) from left to right, are the plucking phases: approach, sticking, slipping, and release. The finger move $\vec{r}_f$ in the same direction as the string $\vec{r}_s$ in plucking phases. Three points are labelled in (d), contact $t_c$ , slipping $t_s$ , and release $t_r$ . Akin to Pavlidou's model, the finger assumed to move in a plane perpendicular to the string length, i.e. XZ. As shown in figure (d), the free vibration of the string formed an ellipse shape. . . . .	16
Figure 2.6.	Contrast to (a) monovision; (b) stereo vision is free from the ambiguity of depth. We can measure the coordinate of any point on the ray $O_L P$ through triangulation of image pairs. . .	17
Figure 2.7.	Single-camera stereoscopic measurement methods. . . . .	19
Figure 3.1.	Segment of a string stretched to a uniform tension. . . . .	21



- Figure 3.2. Suppose we take snapshots of  $w_1(ct - x)$ , the wave that moves rightward, and see how the shape evolve for a period of time. (a) The wave travels in an ideal string (non-dispersive medium). While in (b), the wave travels in a stiff string (dispersive medium). . . . . 23
- Figure 3.3. The massless ring allows the strings to attach without inducing a non-zero horizontal acceleration even though the tensions are distinct. Figure (a) and (b) are drawn in side view. . . . . 24
- Figure 3.4. An ideal string is rigidly fixed at the ends and plucked at one-fifth of string length. (a) The two dashed curves move in the opposite direction with the same shape and velocity; the reflection of the dashed curves are inverted (facing downward). The solid curve is the resultant of two dashed curves. Figure (b) shows the spectrum of mode amplitudes. . . . . 29
- Figure 3.5. Shadows of extended light source. Figure adapted from [36]. . . . . 30
- Figure 3.6. In the bare sensor setup (a), the reflected light rays from any point of the tree are distributed to all sensor pixels. In the pinhole camera (b) and the lens camera (c), we placed an aperture in front of the sensor. Compared to the pinhole camera, the lens camera does not require a huge tradeoff between light intensity and image resolution. . . . . 33
- Figure 3.7. To avoid inversion, the pinhole model (a) rearranged the image plane to the scene side. The resulting image is shown in (b). Using ratios of the triangle (c), we could find the  $v$  coordinate of image  $p$ . . . . . 35
- Figure 3.8. Line [38]. . . . . 37





Figure 3.9.	Plane [39]. . . . .	38
Figure 3.10.	A line intersecting a plane [40]. . . . .	38
Figure 4.1.	Research flowchart. . . . .	43
Figure 5.1.	The measurement setup. This method utilised two coloured shadow images of an object to measure the three-dimensional location. The main components of the setup are coloured light sources, player (fingertip), modified sonometer (string), cloth screen, and camera. However, please note that the elements in this figure are for illustrative purpose only, and the final design of the light source, the sonometer, and the screen may look different from what is depicted. . . . .	47
Figure 5.2.	ProLight PM2B-3LxS-SD. . . . .	51
Figure 5.3.	The lightsource. Two high-power LEDs are glued into the heatsink (in the Figure, it presented as a rectangular bar) using thermal paste. The component diagrams are adapted from [44, 45]. . . . .	52
Figure 5.4.	In Figure (a), the adjustable table is locked. While in (b), the adjustable table is unlocked. Please note, in (b), the 1-1/2" pipe is drilled (about 3/8") and the 3/8" hex nut is glued into the pipe as a port for the lock. . . . .	54
Figure 5.5.	Wood frame with cloth screen. . . . .	55
Figure 5.6.	The layout of the measurement setup (top perspective). . . . .	56



Figure 5.7.	The schematic of one point-like object (PLO) motion measurement system. The big flat plane in the middle represents the cloth screen in Figure 5.1, while the smaller one represents the camera's sensor. The origin of the system is fixed in the centre of the cloth screen plane. . . . .	59
Figure 5.8.	The flowchart of rays-plane-intersection program. . . . .	63
Figure 5.9.	The schematic of fingertip motion measurement setup (top perspective). . . . .	64
Figure 5.10.	The schematic of string motion measurement setup (top perspective). . . . .	66
Figure 5.11.	The flowchart of sensitivity analysis program. . . . .	69
Figure 5.12.	Suppose the value of $z_{lb}$ and $z_{lr}$ is equal, and then we define a new variable $z_{ls}$ to substitute them. This figure shows the absolute sensitivity of the point-like images by varying the $z_{ls}$ . The closer the light sources (blue and red) relative to the screen, indicated by $z_{ls}$ , the higher the sensitivity of system. . . . .	73
Figure 5.13.	The sensitivity of the point-like images by varying the $z_{op}$ . The farther the object's starting position (before moving) relative to the screen, indicated by $z_{op}$ , the higher the sensitivity of system. . . . .	74
Figure 5.14.	The sensitivity of the point-like images by varying the $z_{cl}$ . The closer the camera relative to the screen, indicated by $z_{cl}$ , the higher the sensitivity of system. . . . .	75
Figure 5.15.	The sensitivity of the string images of various $x_{rel}$ . . . . .	80
Figure A.1.	The LED driver. . . . .	94
Figure B.1.	The adjustable table. . . . .	96



Figure B.2.	The cross-section view of the adjustable table shows the	
	locations of the holes. All dimensions are in millimetres. . . .	98
Figure B.3.	The locking knob. . . . .	99

