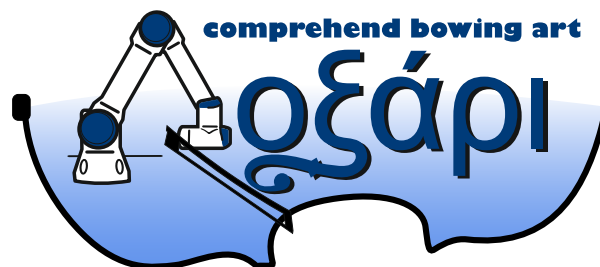


A VERSATILE MONOCHORD SETUP: AN INDUSTRIAL ROBOTIC ARM AS BOWING AND PLUCKING DEVICE

Alexander Mayer, Alessio Lampis

Department of Music Acoustics - Wiener Klangstil (IWK)
mdw - University of Music and Performing Arts Vienna, Austria
mayer@mdw.ac.at, lampis@mdw.ac.at



DEPARTMENT OF
MUSIC ACOUSTICS
WIENER KLANGSTIL

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Abstract

Experiments on the bowed string are often carried out on monochord setups [1] and with specialized bowing machines [2, 3, 4, 5] in order to study the excitation in detail. These setups simplify the equipment with the necessary sensors. Furthermore, by using rigid body monochords, measurement uncertainties can be minimized by eliminating vibrating components such as the resonating body, bridge, neck, etc. When the string is then excited or bowed using a machine, there are further advantages in terms of reproducibility or controllability of the excitation and bowing parameters.

This technical report provides technical details of a monochord built at the acoustic laboratory of the Department of Music Acoustics – Wiener Klangstil (IWK). The advantages of using strain gauge sensors for string vibration analysis are presented and discussed. In contrast to a custom-made bowing machine, however, an industrial robotic arm was used for string excitation, thereby allowing for highly versatile applications. Enclosed detail pictures, circuit diagrams and software flowcharts provide the possibility of simple replication of the setup described.

1 Introduction

In the “Doksari” (Greek for “bow”) projects, at the Department of Music Acoustics, one of the aims is to better understand aspects of playing techniques through experimental measurements. This allows to inform existing physical models of bow-string interaction, thus leading to more accurate numerical simulations. Such simulations may increase our understanding of the link between several playing techniques and the resulting sound.

While numerical simulations are often used to solve complex research problems, the problem definitions tend to be heavily simplified. In this particular bow-string interaction problem, the virtual musical instrument is divided into sections for separate analysis. The partial results can only be meaningfully expanded to form a larger whole if they are validated by experimental measurements. However, in order to enable result comparison, it is also necessary to impose restrictions and to simplify the measurement setup.

The presented setup allows to observe the string vibration at high precision, with the least external influence. In addition, a robotic arm used as a bowing (or plucking) device allows the string to be excited in a precise and reproducible manner. This report is divided into two main chapters. The first describes the hardware of the monochord and the excitation mechanism. The second deals with software for controlling the excitation, the measurement sequence and the recording functionality.

2 Hardware

Considerations regarding stability and strength of a measuring stand must be taken into account when analysing string vibration. With cello strings, an average string tension of around 150 N can be expected, and the supporting structure should be able to withstand this tension without deformation. The supporting structure should also have little or no tendency to vibrate. In addition, it must be large enough to accommodate all the necessary components.

2.1 The monochord setup

The supporting structure is a laboratory grade 781 series optical table from TMC / AMETEK. The table features a steel honeycomb core, resulting in a highly rigid structure of about 30 cm of height. The surface area of the table is approximately 1 m × 2 m, providing enough space to fit a cello string with a scale length of about 70 cm, together with tuning and string termination devices, as well as a

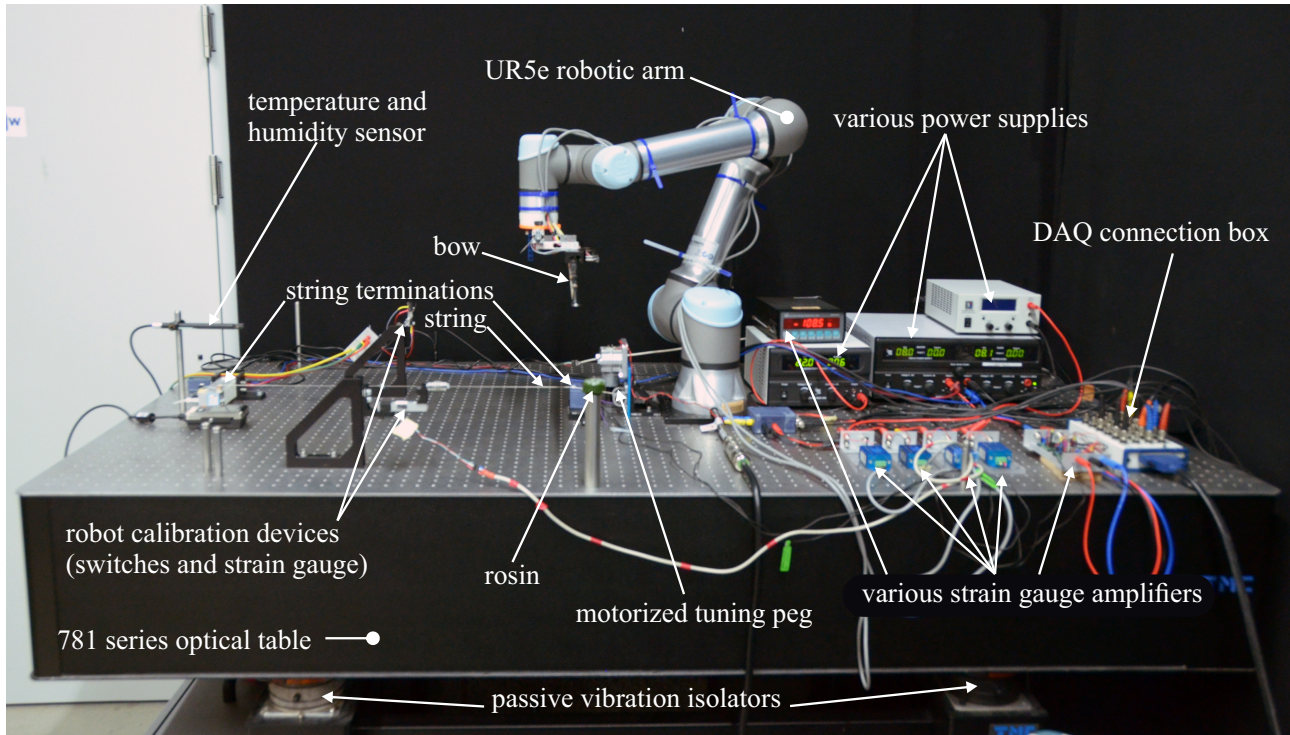


Figure 1: General view of the setup, the string is stretched lengthwise, the Universal Robots UR5 arm sits almost in the centre.

robotic arm. The top is manufactured out of 5 mm thick steel, with the entire surface tapped with a grid of M6 threads. The same brand's leg system provides a stable, pneumatic vibration isolated stand in the laboratory[6].

The monochord consists of two different string terminations. Referring to Figure 1, the right hand-side termination (bridge) includes a two-dimensional vibration sensor using strain gauge technology (see section 2.1.1). On the left-hand side (nut), the termination is made out of a heavy load cell acting as string tension sensor and a two-dimensional vibration sensor using piezoelectric technology (see section 2.1.3).

2.1.1 String termination, bridge

In a previous version of the setup, mechanical parts from Thorlabs were used, that were slightly adapted to hold the sensors of the bridge [7]. However, this setup had some disadvantages. The arrangement prevented the bow from being moved close to the termination. Additionally, the sensors were mounted with too much play, resulting in minor inaccuracies. This termination will be referred to as the "bridge", as the excitation positions along the string are closer to this termination than to the other.

The disadvantages mentioned above led to a custom design, which can also be in part produced using 3D printing technology. A major advantage is that the printed parts are quickly available, easy to modify and can also be subsequently processed. If the MSLA (Masked Stereolithography Apparatus) process is used, it is necessary to ensure that the components are sufficiently cured, otherwise they may warp under load. To ensure high rigidity, the print was made with 100% infill, i.e. solid throughout. The sensors, two 8 mm button load cells, are inserted into a corresponding deepening on the surfaces. A 3D printed wedge transfers the vibration of the string to the sensors. The string tension keeps the wedge in place, and small grooves on its back prevent it to slip off the button load cells. Like on the real cello bridge, the wedge features a semicircular cut-out as a string guide. To ensure that the

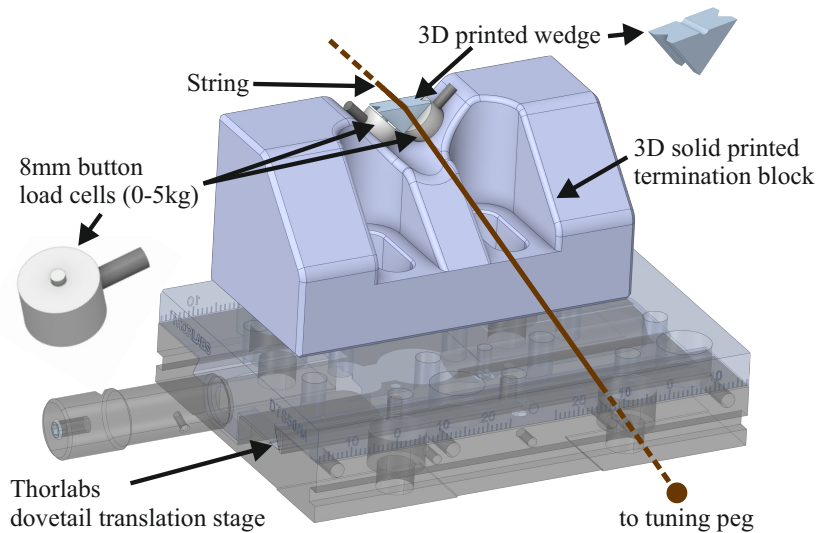


Figure 2: 3D printed end bridge termination block. The translation stage is used to align the string.

string is correctly aligned, the whole termination can be moved using the translation stage (Thorlabs, DTS50/M [8]).

We used Daysensor DYHW-108 load cells. As an alternative, the FC8E-50N [9] sensor from the Chinese manufacturer Forsentek could be used (or any other 50 N, 8 mm button load cell). The maximum load capacity of the load cell accommodates the need for a good sensor's sensitivity, and it guarantees the sensor to withstand the string tension. Both types are very inexpensive and have proven themselves so far. In general, load cells are advantageous for measuring static forces. They are commonly used in slow processes, such as various applications of weight scales. But the frequency behaviour of load cells is primarily determined by their mechanical structure[10], rather than the actual sensors (the strain gauges). In comparison to beam shaped load cells, the button type sensors are assumed to be much more rigid due to their small size and material. Thanks to their arrangement at 45 degrees to the horizontal plane, the signals acquired by both the sensors can be transformed to obtain the force acting in any direction. Comparisons of the measured termination force with equivalent numerical simulations (Figure 3 as an example) show the accuracy of the sensors in terms of frequency and noise content.

2.1.2 DIY strain gauge amplifier / INA128

As the forces measured by the two load cells must cover both dynamic and static force components, a suitable pre-amplifier is also required. Commercially available signal conditioners that provide a frequency band within the audio frequency range are rare to find and usually very expensive. This led to design a custom amplifier. The circuit largely corresponds to the circuit shown in the data sheet for the INA128 instrumentation amplifier IC from Texas Instruments (data sheet Figure 9-2, Optional Trimming of Output Offset Voltage [12]). The resistor referred to as R_G in the data sheet for setting the gain has been replaced with a trimmer resistor to allow for adjustment of the amplification factor. The resistors of the DC offset trim circuit have been increased in order to achieve a wide adjustment range. The circuit has been extended to include appropriate backup capacitors. Because only two channels need to be amplified, no PCB design was required, and the circuit was realized on an electronic matrix board.

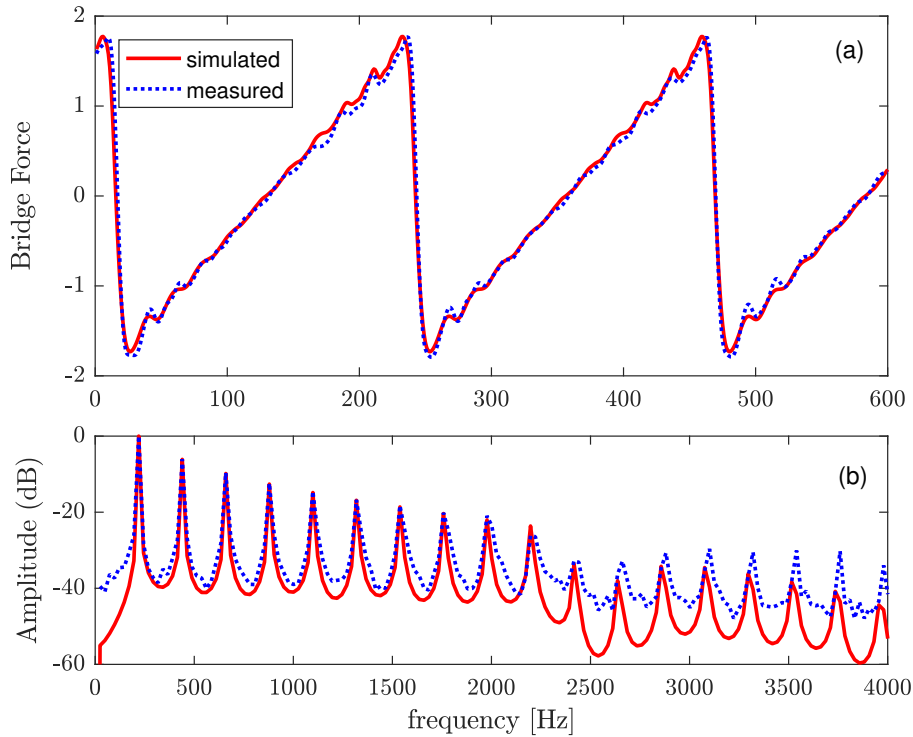


Figure 3: Simulated bridge force for finite-width bow using an elasto-plastic friction model vs. measurement (a), and their amplitude spectra (b) [11]

2.1.3 String termination, nut

As the string forces measured at the bridge provide valuable information, we have also installed a set of sensors at the other termination (nut) shown in Figure 4. Here, the string is not fixed to the optical table, but mounted on a load cell manufactured by Forsentek[13]. This enables the string tension to be measured. This beam load cell is designed to withstand a tension of approximately 2000 N, which is about 20 times higher than the expected string tension. Due to its design, it can be considered a rigid termination. In theory, it should have no influence on string vibration (see section 2.1.5). The Hottinger Baldwin MVD2510 [14] load cell amplifier is used to amplify the load cell signal. The tension reading is displayed on the amplifier to have a constant check of the current string tension.

The nut-sensor is placed piggyback on top of the load cell (see Figure 4). The nut-sensor comprises a foot that has been created using 3D printing technology. The foot holds two piezoelectric crystals that are positioned at a 90° angle to each other and at a 45° angle to the surface of the optical table. The piezoelectric sensors pick up the force of the string via a 3D-printed wedge, allowing for 2-dimensional force measurement. The piezoelectric chips used are made by Thorlabs (see data-sheet [15]) and consist of stacked piezoelectric ceramic layers. In contrast to load cells, these sensors have a higher sensitivity, which also increases the SNR (signal-to-noise ratio). The disadvantage is that static forces cannot be measured.

2.1.4 DIY charge amplifier

The effort required to amplify the signal from a piezoelectric sensor is significantly lower than that required for strain sensors. The piezoelectric sensors can be idealized as a capacitor that changes its electrical charge depending on the mechanical load.

Therefore, a so-called charge amplifier is used as first amplification stage (see Figure 5). In this special form of inverting amplifier circuit, the capacitor $C1$ becomes the primary feedback compon-

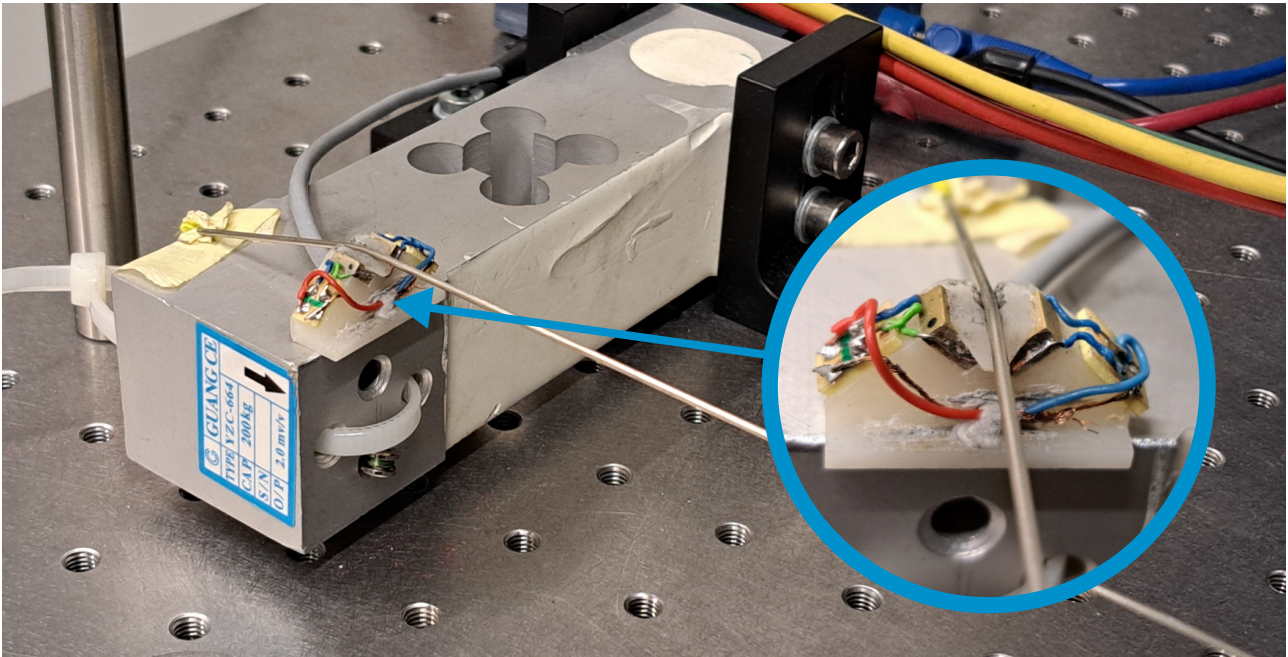


Figure 4: String termination with piezoelectric sensors (Thorlabs TA0505D024 [15]) for measuring the string vibration placed on top of a beam load cell (Forsentek FNL-200kg [13]) for measuring the string tension.

ent. The relatively high-impedance resistor $R1$ is used to eliminate unwanted offset drifts caused by leakage currents. Since a high-pass filter is formed by $C1$ and $R1$, the components must be suitably dimensioned to ensure good and broadband signal transmission. When selecting the operational amplifier, attention should be paid to a high input resistance and low offset drift. Most modern FET input operational amplifiers have a sufficiently low offset drift and input currents in the range of μ -amperes. For this application, the TL08xx amplifier, but also general purpose op amps like the LM358 will work.

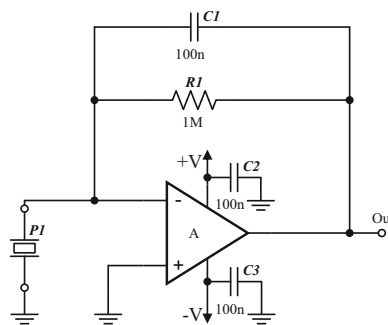


Figure 5: Charge amplifier for signal conditioning of the piezoelectric sensor based on the design of [16]

2.1.5 Termination sensor verification

Since two different technologies were used, a method to compare the sensors' frequency responses and their time domain signals and was needed. To assess the setup accuracy, it is recommended to conduct a test with the sensors installed on the monochord setup and the string tensioned, as done during normal operation. The wire-breaking method was used to analyse the response to a step force

(see 1973 by W. Reinicke [17]). The excitation point was chosen exactly in the middle between the two termination points. The plucking-wire used was a stainless steel spring wire, type 1.4310 [18] with a diameter of 0.03 mm. The direction of the initial force excited by the wire was kept in parallel to the table surface, i.e. the main bowing direction. The very first response cycles to the pluck are plotted in Figure 6. The sensors are calibrated in Newton using reference weights. In Figure 6(a), the low-frequency signal content was not filtered in order to indicate the two different signals behaviour in reacting to quasi static forces — the signal captured by the piezoelectric sensor will slowly change to a zero symmetric signal. In Figure 6(b), the two responses are superimposed using a high-pass filter on the signal captured by the load cells. The differences in the signal are hardly noticeable. Moreover, the small variation of force just after the jumps suggests the terminations to be rigid [19], while the oscillating overshoot is caused by the dispersion effect of the string. A spectral comparison is given in Figure 7. The higher signal-to-noise ratio of the piezoelectric sensor signal (red) can be clearly recognized here. Overall, the frequency bandwidth of both sensor systems are considered sufficient.

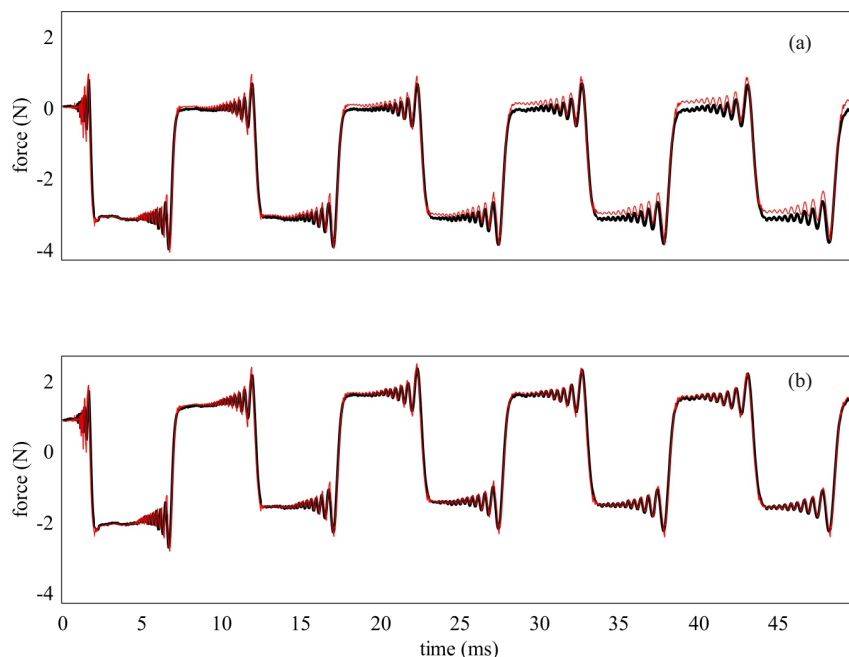


Figure 6: Pluck response of a G cello string, obtained by breaking a thin wire in the middle of the string. The plucked-string signals are captured by the load cells (black curves) and the piezoelectric crystals (red curves). The force signals are scaled to be displayed in Newtons.

2.2 The Bowing Machine / robotic arm

The UR5e robotic arm we used is a collaborative industrial robot manufactured by the Danish company Universal Robots [20]. The robot has six degrees of freedom, corresponding to six joints. The maximum reach is 850 mm from the base origin with a payload of up to 5 kg. Because of the collaborative nature of this robotic arm, it can be used without a protective fence due to its built-in safety features. The end-effector speed is typically in the order of 1 m/s and a stated pose repeatability in the range of ± 0.003 mm, making it suitable for most bowing requirements. In general, the UR5e robotic arm moves quietly and smoothly. However, despite operating within the technical limits, when performing rapid changes in direction, the entire structure can shake because the arm mass is much higher to the one of a human. For this reason, it is important to exercise caution when programming

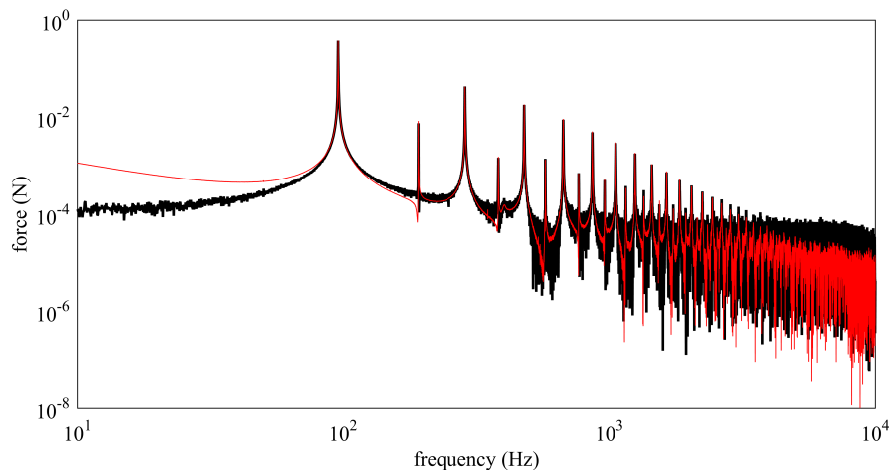


Figure 7: Spectra of the pluck response of a G cello string, obtained by breaking a thin wire in the middle of the string. The plucked-string signals are captured by the load cells (black curves) and the piezo-crystals (red curves).

the movements. The robotic arm can be easily integrated into measurement systems. It can communicate with external devices either directly via digital or via analog input and output ports, or via network integration.

2.3 The bow holder and related sensors

Reused from other projects, a 3D-printed part connects the robot last joint with the bow-holding setup. A 20 cm long extruded aluminium profile (“aluminium bar” in Figure 8) serves as an extension where to mount two low cost load cell sensors type FHD-5kg [21]. Two FP02 plate holders from Thorlabs are mounted on each load cell to ensure stable mounting of the bow. To ensure the bow being stroked as vibration-free as possible, it was mounted on the mechanics of a windscreen wiper arm. Instead of the rubber wiper blade, the bow was clamped in. This choice allows an almost vibration-free but still quite flexible installation, and ensure a more homogeneous distribution of forces along the bow stick.

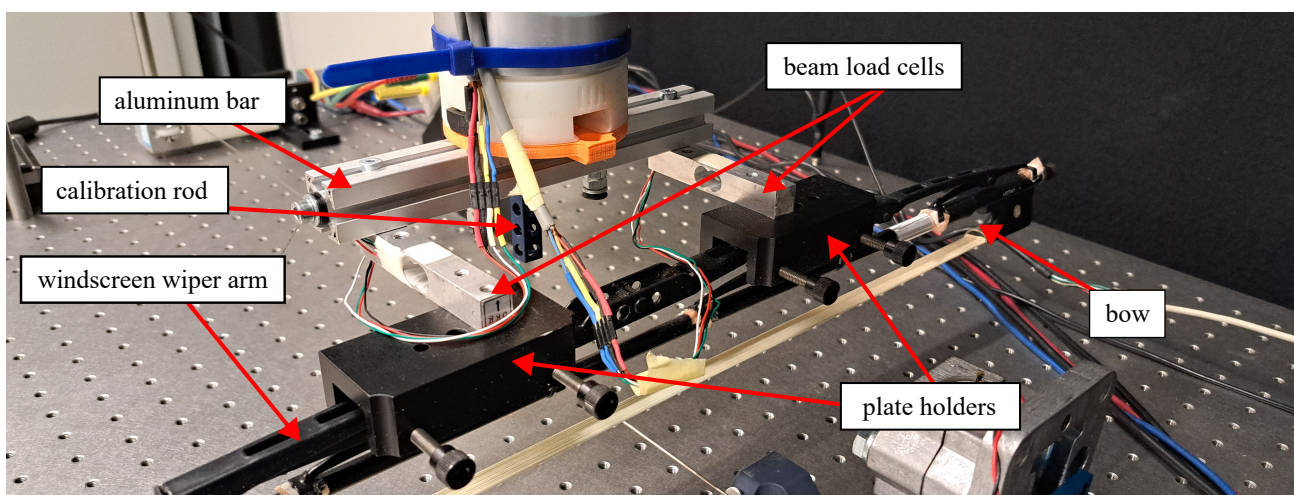


Figure 8: Bow holder system with sensors for measuring the bow force.

2.3.1 DY510 Load Cell Amplifier / Maranon DY510

This very compact and very reasonably priced amplifier was purchased from Amazon. Unfortunately, there is no data sheet for this signal amplifier. It provides sufficient and adjustable gain and offset. After a few tests, however, the general usability and stability of the device was verified. As this type has an integrated low-pass filter, it is only suitable for measuring virtually static forces. In the setup, the signals of the three bow related force sensors are amplified using this amplifier, which performed well for the quasi-static forces typical of bow forces.

2.4 The motorized tuning peg

To provide the possibility to automatically tune the string, a motorized tuning peg was developed (see Figure 9). It consists of a supporting plate (qfix, 100x100x5) which is covered with a grid of mounting holes and M6 threads. On this plate, the pillow blocks that house the bearings are mounted. This type of pillow block bearing does not require precise alignment because the ball bearings are inserted in a slightly rotatable configuration. The inserted axle aligns the bearings correctly. An 8 mm axle serves as the actual peg, and it is featured with a brass gear. On a geared DC Motor from RS-Components (Stock No: 752-1983) a worm-gear drives the axle with 1:10 gear ratio. This mechanism ensures the desired string tension to be easily achieved. Moreover, when the motor is switched off, the peg is constrained from rotating due to the worm-gear locks. A L298N dual H-bridge driver module is used to control the motor speed and direction. The motorized tuning peg is fixed on the table surface using a right-angle mounting plate by Thorlabs (AP90/M). The signals to control the motor are generated by software (see section 3.2) and output through the NI PCI-6251 DAQ.

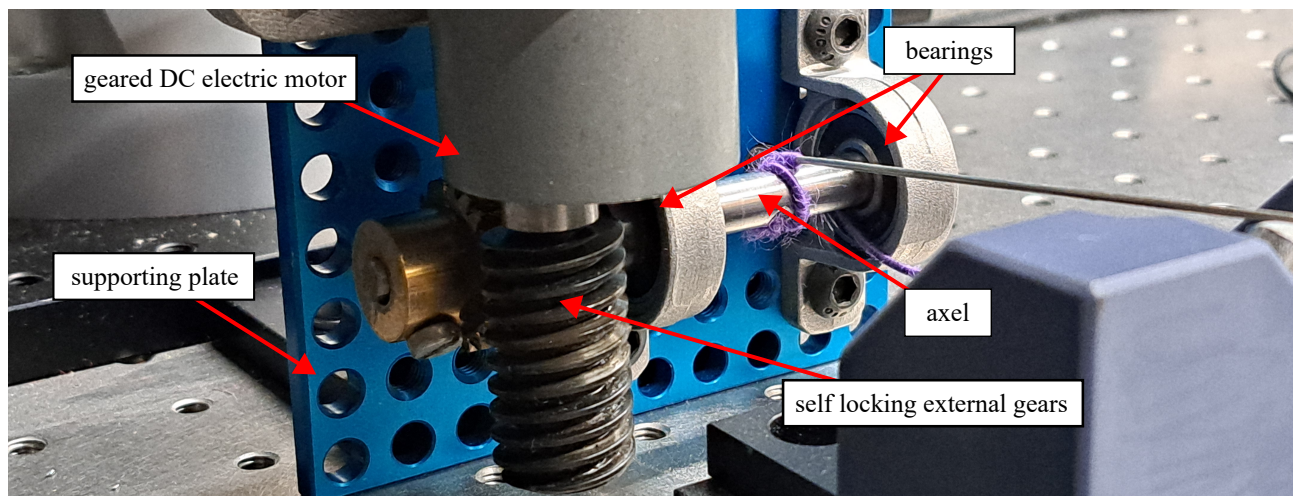


Figure 9: The mechanic components of the automatic tuning module

2.5 The calibration devices

Although the robot arm used has a very high level of precision and repeatability, position errors may accumulate due to rounding processes in robot programs. To counteract this, the robot arm is moved to a calibration position at periodic intervals. Once there, the limit switches (Figure 10) are actuated via the calibration rod mounted on the side of the bow (see Figure 8). The switching signal is picked up directly by the robot control electronics and processed further in the robot control software.

An additional beam load cell was also installed, as the bow hair tension is also to be checked regularly and the bow sensors calibrated. The bow is automatically pressed against a roller (see

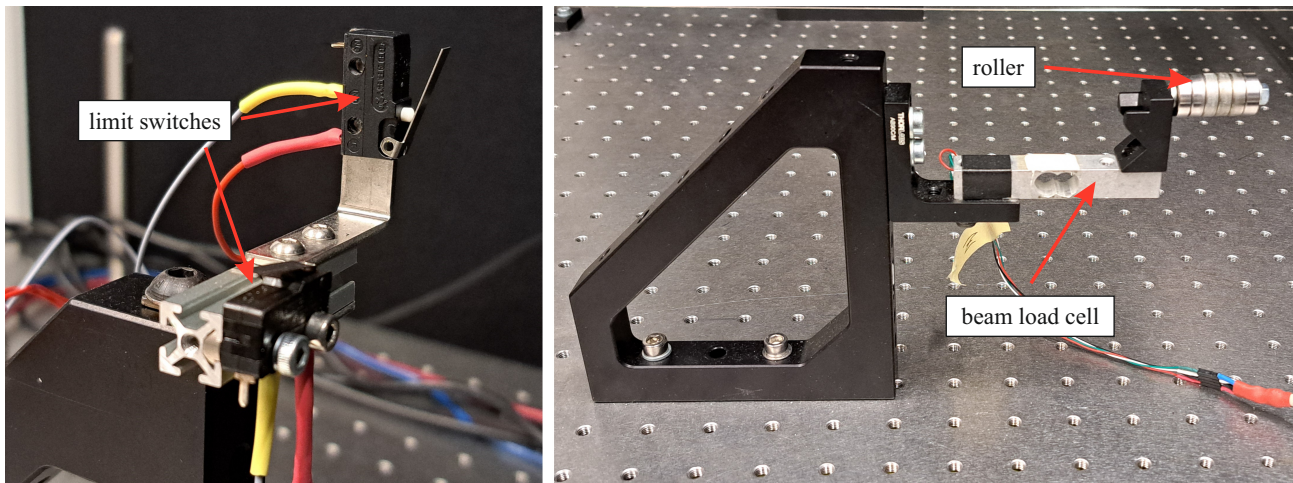


Figure 10: left: calibration device for positioning the robotic arm (left) and for the bow force (right).

Figure 10, on the right) mounted on such a load cell, and the downward force measured. In the plot presented in Figure 11 the force measured by the two load cells on the robot and the load cell with the roller are displayed as a function of the position along the bow. The force plotted on the right-hand side is calculated by adding the signals from the two sensors mounted on the bow. The graph in the middle shows the linear relationship between the two measurements and proves the correct force calculation of the bow-force along the whole bow length.

The load cell (FHD-5kg), as well the signal conditioner (DI510), are of the same type as for the bow measurement. Both calibration tools (switches and load cell with roller) are mounted on the optical table using VB01A/M - 6" vertical brackets from Thorlabs.

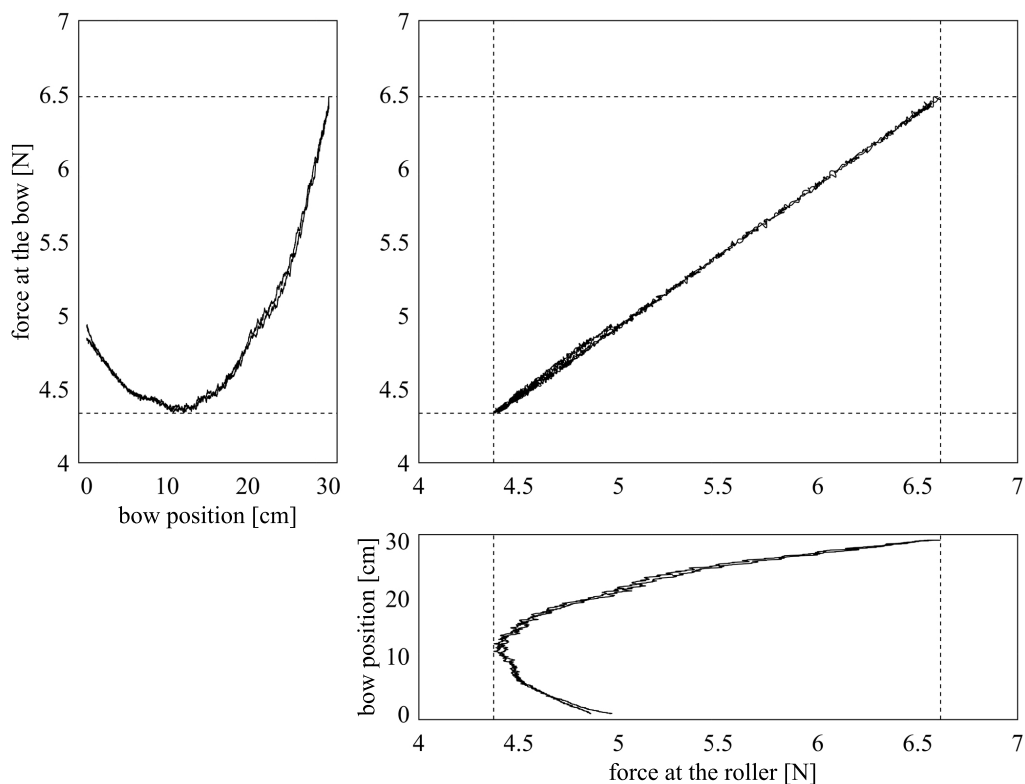


Figure 11: force measured with the two beam load cells versus the measurement on the calibration device

2.6 Signal wiring

As already mentioned, the DAQ device used is a PCI-6251 data acquisition card from NI. The benefit of using this device is to convert static input signals to digital. It is also easy to implement this hardware into the programming software LabVIEW of the same company. The high number of analog inputs in conjunction with digital I/O, as well the availability of counters, makes it a preferred I/O device, even it is already outdated. NI offers a wide range of modern substitutes which should normally work with the same software. Figure 12 presents the signal wiring. For simplification, the necessary power lines and lab power supply units are not displayed. The schematic can be split into three main sections: a) Analog In (green and blue), b) Digital I/O (magenta) and c) LAN / RTDE (orange). The analog signal lines are all connected via BNC cables to the NI BNC-2111 connector block (AI0-7). The motor driver unit is connected to two digital ports (BNC-2111 PFI 0/P1.0, PFI 2/P1.2) for direction and to counter-out (BNC-2111 CTR 0 OUT) for speed control via pulse with modulation. Communication between the PC (LabVIEW Software) and the robot is established over TCP/IP and the RTDE protocol [22, 23]. This data exchange protocol is used to capture the current robot end-effector position in relation to the robot base. It also exchanges boolean and integer variables for process control (see Figures 13 and 14). Only the limit switches are connected directly to the UR5e input ports.

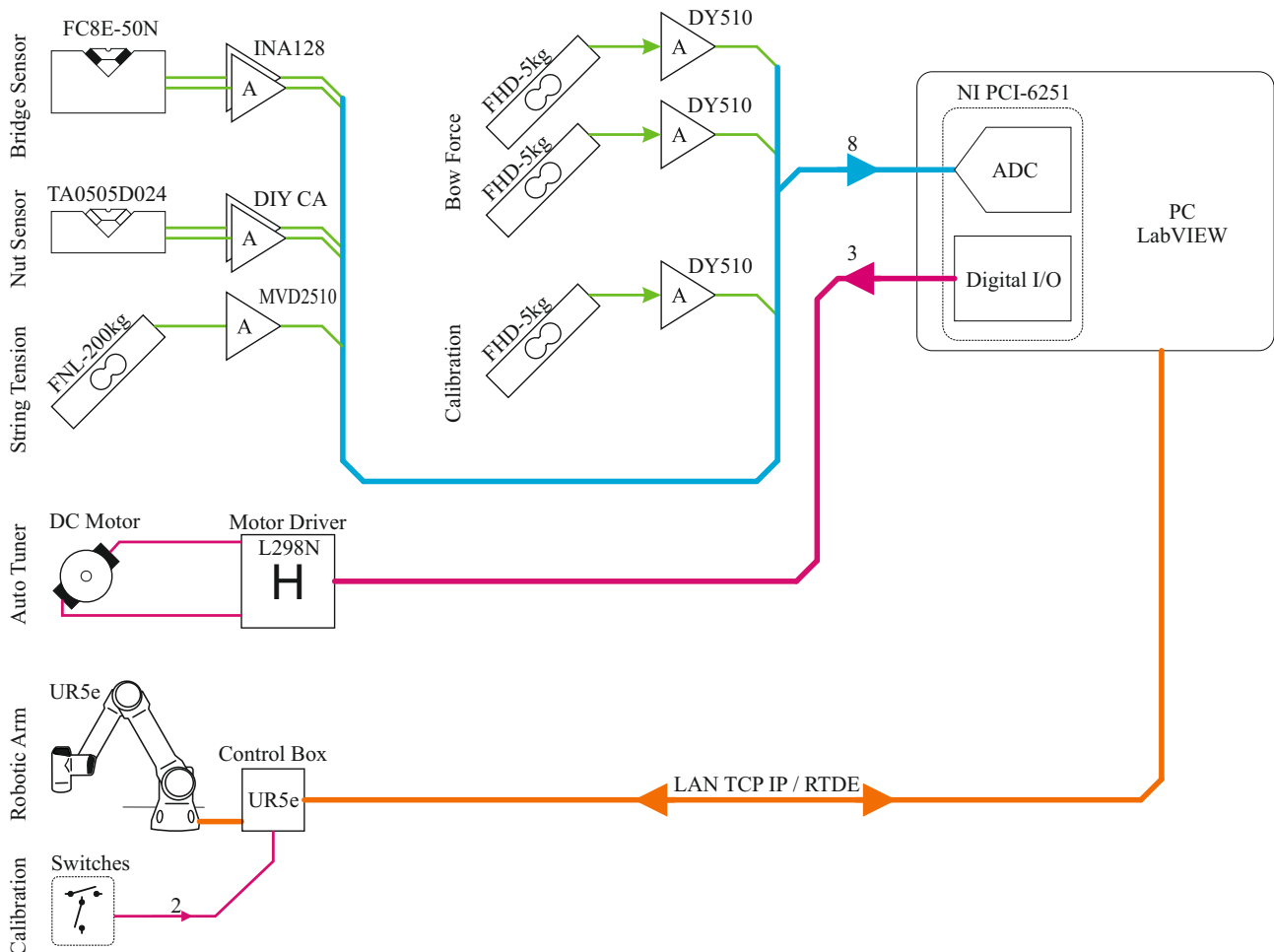


Figure 12: Schematic of the electrical signals and data connections of the setup: green/blue: analog single channel/bus, magenta: digital lines/bus, orange: LAN

3 Software

In general, any multichannel recording software and audio interface could be used to record the various sensor signals. If also static sensor values are of interest, one has to select an interface with DC coupling (which most audio interfaces will not offer).

A multi-functional solution was developed using the graphical systems engineering software NI LabVIEW to automatically obtain bowing data with a high variability of bowing parameters. The DAQ device offers a wide range of DC-coupled input and output channels, both analog and digital, and can be easily integrated into LabVIEW. The robot program serves as the main program, controlling the robot arm and managing the status and functions of the recording software.

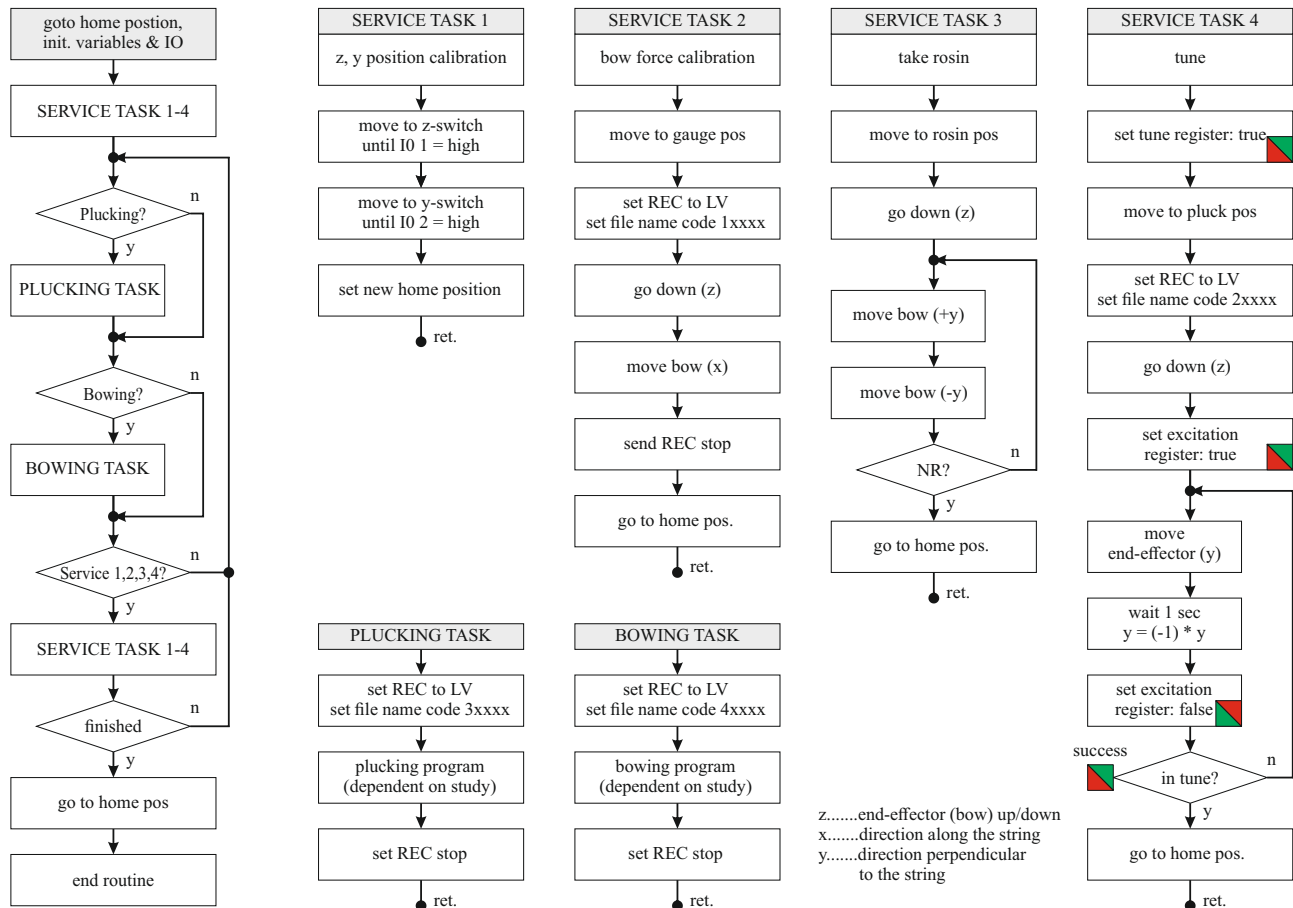


Figure 13: Simplified flow chart of the UR5e Polyscope program

3.1 The UR5e Program

For most of the tasks, the internal software PolyScope is more than sufficient for commanding the robot. The programming environment can be opened on the teach pendant with a graphical user interface. The user can define robot initial settings, connections, and much more (see PolyScope Basics in [24]). The robot movements can be programmed depending on the type of study. Studies that need to systematically control the bowing parameters, such as different bow accelerations, bow speeds, angles, or positions along the string, are possible with this setup. Moreover, having this variability, it makes sense to program a whole test loop, e.g. altering one by one of the parameter mentioned (see e.g. [7]) so that automatic acquisitions for collecting bowing data in high resolution are possible. To simplify the post-processing, the robot program controls the recording software by

sending start and stop triggers for recording. In addition, it sends integer codes that correspond to the current movement that are used in the filenames of the recordings. These integer codes are sent via the network connection and the RTDE protocol [22]. Regularly called service tasks in between the measurement tasks ensure reproducible excitation for long-term measurements. The flowchart in Figure 13 illustrates the basic program sequence.

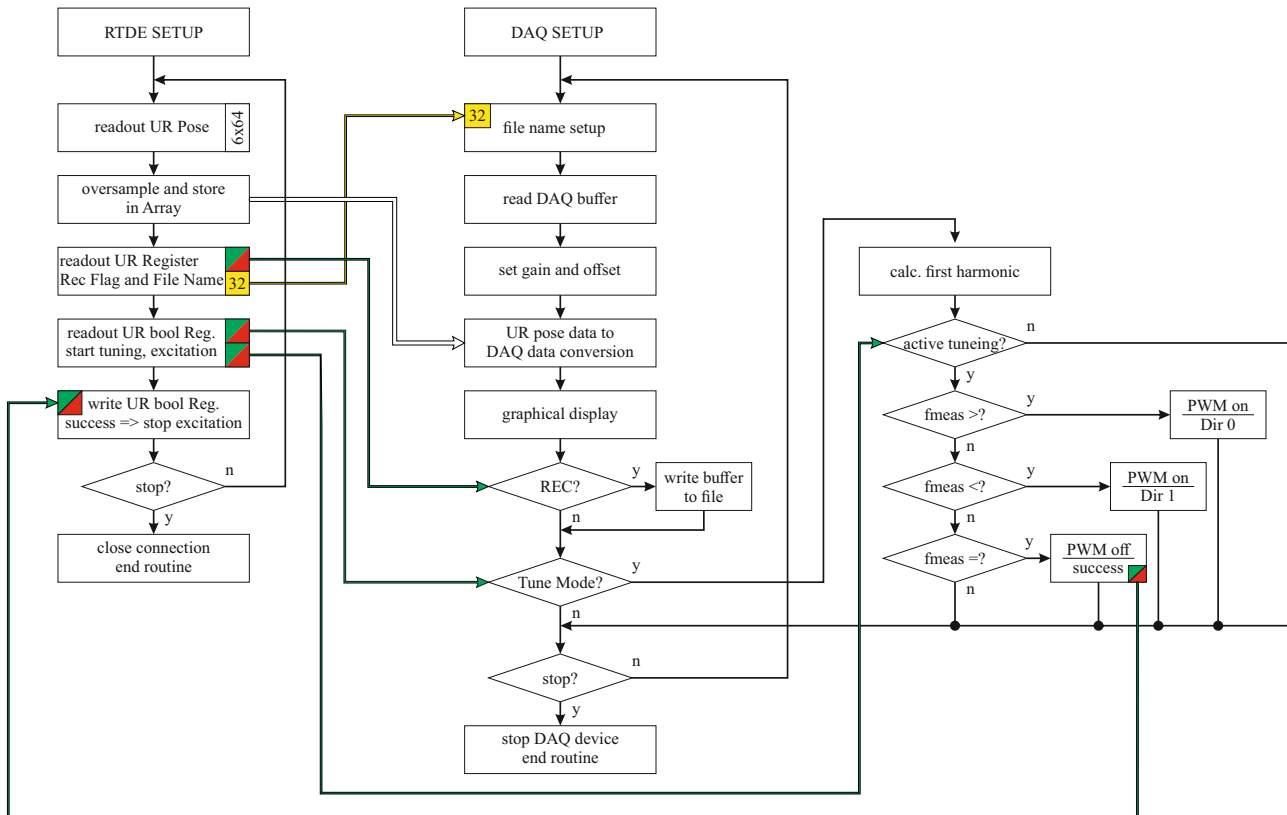


Figure 14: Simplified flow chart of the NI LabVIEW recording software.

3.2 The LabVIEW DAQ Software

The LabVIEW software consists of two “while” loops executed in parallel. Communication with the robot takes place in the first loop. The network connection is used to transfer information via communication registers. As can be seen in the flow chart (Figure 14, first column), the end-effector position is transmitted as a 6 dimensions vector (3 position values and 3 angles) with 64 bits each. An integer value with 32-bit resolution is used to encode the filename, boolean registers are used to switch the auto-tuner on and off. The transmission rate is 125 times per second. To encode the position data together with the sensor data in a multi-channels wav file, this position data is upsampled.

The main task of the second loop is to integrate the DAQ device and query the data. This is done at a sampling rate of 50 kS/s, with a buffer size of 2000 samples and 8 channels. As shown in the flowchart, the data can be scaled and unwanted offsets can be zeroed using a simple function. In addition, 6 channels containing the position data (Cartesian coordinates and joint angles of the end-effector), are appended to this data stream.

When the robot recording triggers arrive, the data buffer is written to a wav file. If service task 4 “tuning” is called by the robot program, an additional program branch is executed within the data acquisition loop. This branch calculates the spectrum from a plucked string signal on one pre-selected channel, and determines the fundamental frequency of vibration. When the string is excited by the

robot, the control registers “excitation” activates the tuning process. The fundamental frequency is compared to a target frequency. The tuning motor moves into a direction depending on the difference with the target. After a waiting-time specified in the robot program, the control register of “excitation” is set back to “false”. The tuning process continues after a new excitation stroke of the robot. This guarantees that the auto-tuning process is only carried out when the string is actually vibrating and valid frequency data can be determined. As a safety feature, a certain user defined tension value must not be exceeded. This process will be repeated as long as the desired frequency is achieved within a user-defined precision. The NI LabVIEW program then sets the “success” register to “true”, the robot program will react and close the tuning loop.

4 CONCLUSIONS

The setup we presented has demonstrated its ability to excite a string and measure its response with a high degree of reproducibility. Additional software and hardware like the tuning process have been tested and proved in a series of tests under different conditions. The high degree of automation allows high resolution measurements without efforts for the experimenters. More details on the software as well 3D-models of the printed parts can be supplied on demand.

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A VERSATILE MONOCHORD SETUP: AN INDUSTRIAL ROBOTIC ARM AS BOWING AND
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