DXSystem - Dynamixel System Library User Guide

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September 2015

Git repository can be found in `https://github.com/KM-RoBoTa/DXSystem.git`.

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1.1 Dynamixel Motors

1.1.1 Communication - Half-Duplex

Dynamixel motors use half duplex serial communication, where data can be transmitted in both directions along the same wire. This protocol has the advantage of communicating with multiple devices through a single bus. However, this means that data cannot be transmitted and received simultaneously, and that only one device can transmit signals at a time. Understanding this limitation is crucial so as to avoid timeout and corruption when communicating with Dynamixel motors.

1.1.2 Communication - RS485 and TTL

There are two main serial communication protocols that dynamixel motors use, depending on the motor model - RS485 (4-pin) and TTL (3-pin). Half duplex operation is used for both communications (i.e. native TTL/UART on single-board computers and microcontrollers cannot directly communicate with Dynamixel motors without an intermediate component or a mutex).

1.1.3 Fine Motor Control - PID and Compliance Slope/Margin

Different dynamixel motor models possess different fine control mechanisms. MX-series motors generally possess closed loop controls (PID), while RX-28 and AX-12 rely on compliance margin and slope settings to control the flexibility of motors. Definitions of these terms can be found in the documentations of the respective motor models.

1.2 Dynamixel SDK

The Dynamixel SDK/API is available for Windows and Linux platforms. The SDK is written in C (although the Windows SDK is designed for use with Visual Studio). The SDK can also be used for other unsupported platforms by setting up the platform-dependent source (`dxl_hal.c/.h` files); the `dynamixel.c/.h` file is platform independent.

1.2.1 Control Table - EEPROM and RAM

Each motor possesses a control table that contains data pertaining to its status and operations. The control table may vary for different models, where some addresses (corresponding to certain functions) may be missing or may define different parameters. Notably, MX series motors have additional registers (68 and above) not found in the AX and RX motors.
In our interface (as will be further described later), the control table is coded in the `control_table_constants.h` header file for easy reference and access.

2 Changes to SDK/API

2.1 Object-Oriented Modifications - DXLHAL and dynamixelClass

The USB2Dynamixel SDK for Linux platforms was used as the basis for this work. However, as the SDK uses global variables when connecting to the device (in dxl_hal.c), the program is limited to 1 USB-to-Dynamixel device. To isolate these settings for individual ports, the functions of the SDK has been converted into methods of a class. Hence, an instance for each serial port corresponds to its own object, and there is no interference between the different ports. All other features are the same. However, as will be expounded later, a higher abstraction layer that introduces newly implemented classes and functions has been introduced. Hence, direct access into the object-oriented variant of this SDK is not necessary.

2.2 Queue Bytes in Dynamixel SDK

The SDK provided supports reading and writing bytes to the motor's control table. However, queueing instructions, which allows for (almost) simultaneous transmission to motors, is not provided by the SDK. The functionality to queue bytes and words has been added, in a similar fashion to reading and writing. The execute function, which is the signal to transmit all queued instructions, has also been introduced.

2.3 Changes to Writing Bytes for Speed

Writing bytes to the Dynamixel motors can be achieved by using the instructions INST_WRITE and INST_SYNC_WRITE. The SDK recommends using INST_WRITE for writing to a single motor and INST_SYNC_WRITE for simultaneous control to multiple motor. However, analysis of execution time (in C++) revealed that the time taken to process INST_SYNC_WRITE is significantly faster than INST_WRITE (15 μs vs 1-5 ms). Additionally, INST_SYNC_WRITE is also capable of communicating with only 1 motor.
The main drawback of INST_SYNC_WRITE is the lack of a status return packet, which would return information such as the error bit on the individual motors. Nevertheless, noting that the error bits returned is usually 0 (for a well-built and well-designed system/program) and that they can also be received through the read command as part of a closed feedback loop, the status return packet from writing is not essential. Given these information, it seems that the use of INST_SYNC_WRITE is more advantageous than INST_WRITE, even when writing to a single motor. Hence, the Dynamixel SDK has been modified to replace INST_WRITE with INST_SYNC_WRITE. (On this note, it is generally recommended to perform a read function after writing to obtain the status packet.)

2.4 Implementing Bulk Read for MX Motors

In the latest update to the Dynamixel communication protocol, the instruction INST_BULK_READ has been introduced to the MX-series motors. This instruction allows for reading bytes of multiple motors through a single instruction, minimizing the amount of overhead and packet transmission. The use of bulk read has been incorporated into our modified SDK. However, INST_BULK_READ is only recognized by MX-series motors. To ensure compatibility with non-MX models, the bulk read function within the modified SDK has different behaviors depending on the motor model detected. For the MX-series, the corresponding motor IDs will be incorporated into the transmission packet as part of INST_BULK_READ. For all other motor models, the function is equivalent to sequential INST_READ. The function is also able to handle a system comprising a mixture of MX and non-MX motors.
To simplify the behavior and use of bulk read, we limited it to reading the same address(es) across all motors. The INST_BULK_READ allows for reading different addresses for different motors (e.g. reading position from Motor 1 and speed from Motor 2), but not multiple, non-consecutive addresses on a single motor (e.g. voltage and position from a single motor). The INST_BULK_READ is also not limited to reading from all motors within the system (i.e. selective reading is possible). But since we are generally interested in information on the same parameter across all motors within a closed feedback loop, the above simplification is justified. The bulk read function allows for reading a single byte or two consecutive bytes (i.e. a word). (Reading four consecutive bytes (i.e. two words) has also been implemented, where the information returned is a concatenation of two vectors, each containing information of a two-byte parameter (e.g. position and speed, which are two-byte parameters located next to each other on the control table). However, this feature is subsequently not used, to simplify the functions and features of the library.)

3 Library with New Classes

3.1 Higher Abstraction Layer

While the USB2Dynamixel SDK helps encapsulate the implementation details between the controller and the firmware of the motors, it still requires technical knowledge of the control table and specifications of the motor. The goal of this work is to create a higher abstraction layer that directly implements common functions of the motor, such as configuring the system and setting its position and speed.

3.2 Hierarchy

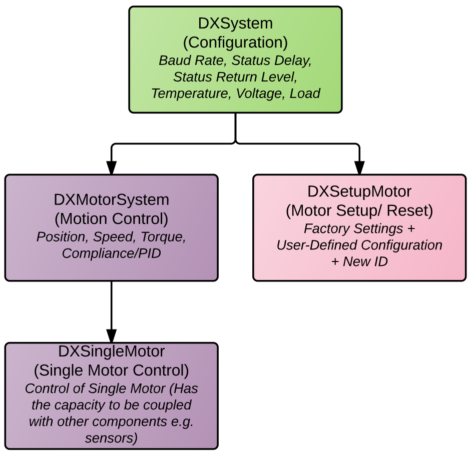

DXSystem
(Configuration)
Baud Rate, Status Delay, Status Return Level, Temperature, Voltage, Load
DXMotorSystem
(Motion Control)
Position, Speed, Torque, Compliance/PID
DXSetupMotor
(Motor Setup/ Reset)
Factory Settings + User-Defined Configuration + New ID
DXSingleMotor
(Single Motor Control)
Control of Single Motor (Has the capacity to be coupled with other components e.g. sensors)

Figure 1: Hierarchy of the classes introduced in the new SDK

In the new SDK, the new classes introduced are:

- `DXSystem` (Superclass) - for basic configuration of the system of motors; contains an object corresponding to the modified USB2Dynamixel SDK
- `DXMotorSystem` (Subclass of `DXSystem`) - adds functions for common motor controls (position, speed and torque control)
- `DXSingleMotor` (Subclass of `DXMotorSystem`) - limits the functions on `DXMotorSystem` to a single motor
- `DXSetupMotor` (Subclass of `DXSystem`) - for resetting and reconfiguring motors to project specifications

3.3 Considerations and Limitations

The functions were developed and tested for the following motors - MX-106, MX-64, MX-28, RX-28, RX-24F and AX-12A. (other motor models are also supported, but not extensively tested.) Newer Dynamixel motors may be used, on the condition that their control table formats does not vary from either the AX/RX-series or the MX-series motors. (E.g., if the control table addresses corresponding to position and speed are the same, functions controlling position and speed can be used. In particular, certain MX motors may have the order of PID registers on the control table swapped, which may result in erroneous behavior.) However, the specifications for these motors must be updated in the `DModelDetails` files.
The functions were also developed and tested for Joint Mode. While alternative modes (Wheel Mode and Multi-Turn Mode) has been taken into account, further tests are required to ensure robustness.
Attempts were made to optimize the functions for memory usage and efficiency. For most settings (with the exception of some parameters such as baud rate, status return level and status delay time, as will be touched on in Section 4), the user can choose between writing to a single motor or writing to all motors. When writing to a large number of motors, writing to all would be more efficient (on the communication level) than looping to write on the motors individually.

3.4 Other Functions and Headers

3.4.1 DModelDetails - Hard-Coding Specifications of Motors

Functions in `DModelDetails` provide details on the specifications for the respective motor models. Most of the motor models have been coded in the respective files. To establish support for other Dynamixel motors, the functions within `DModelDetails` have to be updated with the specifications of the respective model.

3.4.2 Control Table Constants - Macros for Control Table Addresses

The header file `control_table_constants.h` contains macros that matches the control table attributes to their respective numerical addresses. As such, the different addresses on the control table can be accessed using the symbolic name, omitting the need for technical knowledge of the control table addresses. The addresses contain the prefix "P_" (following the convention put forth within the sample code of the Dynamixel SDK). These macros should correspond to the mapping on the motor's control table and hence should not be changed.
Some addresses may be used in more than one macro, since different motors may use the same address number for different attributes. Furthermore, some of the attributes may not exist for certain motor models (e.g. AX and RX motors do not have PID control). As the header file does not check for motor model, the addresses should be called properly. (Using functions in `DModelDefailts` to check for capabilities, such as PID/compliance settings, is strongly encouraged.) In the event that the control table has been changed in newer Dynamixel motor models, it is recommended to include the mappings in this file, but not delete any of the previous entry to ensure backward compatibility.

3.4.3 DConstants - User-Defined Macros for Motor Settings

The header file `dconstants.h` defines "constants" (as macros) that may be frequently used. Some of the constants are states, i.e. constants with symbolic names defined with an arbitrary number, for use as settings and logical comparisons.
None of these constants should be changed. In the situation that new constants need to be introduced, users are advised to add them to the file `src/user_settings.h` instead.

4 Main Functions

(To demonstrate the use of functions, the variable `d` is used to denote a `DXMotorSystem` object, `ds` to denote a `DXSingleMotor` object and `dsetup` to denote a `DXSetupMotor` object. The superclass `DXSystem` would hardly be used, since its subclass inherits almost all its functions.)

4.1 Configuring with DXSystem (superclass)

The `DXSystem` possesses functions within the following groups (under modules in the complete Doxygen documentation) - motor status getters, motor configuration settings, motor reference information and manual adjustments.
Its subclasses, `DXMotorSystem`, `DXSetupMotor` and `DXSingleMotor`, inherit `DXSystem` functions. (However, some functions are protected and hence inaccessible for `DXSingleMotor` objects.)
As the capabilities of `DXSystem` is limited, instantiating a `DXSystem` object is generally discouraged. Its subclasses should be used instead.

4.1.1 Motor Status Getters

These functions can be used to obtain the current load, temperature and voltage of a motor in the system.

```
int load = d.getLoad(motor_number);
int temperature = d.getTemperature(motor_number);
int voltage = d.getVoltage(motor_number);
```

(The returned values are the digital values as encoded in the control table.)
Specifically for load, we can also read this parameter across all motors.

```
vector<int> all_loads = d.getAllLoad();
```

(Note: The motor's 'load' may not necessarily be proportional to the force/torque on the motor. In its implementation, it is loosely related to the current consumption and the differentce between goal and current position on the motor. Further characterization is required to determine the relation between this parameter and the 'true load' on the motor.)

4.1.2 Motor Configuration Settings

These functions can be used to set or read the configuration settings (for temperature and voltage operating limits, status return level and delay, and baud rate) on the motors.
Maximum Temperature:
(The recommended max temperature is 70-80°C, depending on the material of the motor body, and should not be changed.)

```
d.setMaxTemperature(motor_number, max_temperature);
int max_temperature = d.getMaxTemperature(motor_number);
```

Voltage Limits:

```
d.setVoltageLimits(motor_number, volt_lower_limit, volt_upper_limit);
int volt_lower_limit = d.getMinVoltage(motor_number);
int volt_upper_limit = d.getMaxVoltage(motor_number);
```

Set all

```
d.setAllMaxTemperature(v_max_temperature);
d.setAllVoltageLimits(v_volt_lower_limit, v_volt_upper_limit);
```

System Delay Time, Status Return Level and Baud Rate are also settings that can be changed, but the changes have to be made across all motors. (These settings should be thought of as global across all motors, as differing settings may cause unpredictable behavior.)
System Delay Time (the amount of time delay between instruction packet transmitted and status packet received):

```
d.setAllDelay(delay_time);
int delay_time = d.getDelay(motor_number);
```

Status Return Level (corresponding to the settings for when status packet is given):

```
d.setAllStatusReturnLevel(SRL);
int SRL = d.getStatusReturnLevel(motor_number);
```

Baud Rate:
(When baud rate is changed, the port is automatically reopened at the new baud rate by the function.)

```
d.setAllBaudRate(baud_rate);
int baud_rate = d.getBaudRate(motor_number);
```

4.1.3 Motor Referencing Information

The following functions may be used to obtain the model and native ID (on the control table) of individual motors, and the total number of motors detected on the port.

```
int motor_model = d.getModel(motor_number);
int num_motors = d.getNumMotors();
int dxl_ID = d.motorNum2id(motor_number);
int motor_number = d.id2motorNum(dxl_ID);
```

Note: In the implementation of the library, we abstracted the use of ID (on the registers) and replaced it with motor number for referencing (i.e. always starting from 0, and enumerated in increasing order of the IDs detected; doing this reduces the need for users to store their IDs.)

4.1.4 Other Generic System Functions

These functions are mainly used for initializing and checking the `DXSystem` object.
Upon creating a `DXSystem` object, it is possible to check if the system has been initialized successfully using the following function

```
if (d.isInitialized()) ...
```

During setup, if the baud rate has changed, communication with the motors will be disrupted. To re-establish the communication, the device should be re-opened with the new baud rate set. The following function facilitates the re-opening and initializing of the port at the new baud rate

```
d.reopenPort(new_baud_rate);
```

Changing the baud rate (using `setBaudRate`) would also automatically call `reopenPort`.
Upon the end of motor setup, the EEPROM can be locked to prevent any further changes to the settings. However, upon locking, the EEPROM can only be unlocked and changed after restarting the system (i.e. unplug and replug the power supply to the motors). Locking EEPROM of all motors can be done with the following function.

```
d.lockEEPROM();
```

For troubleshooting, the motor number of respective motors has to be known. The following function runs a sequence that helps to identify the motor numbers by lighting up the LEDs in turn. The sequence is executed on the console, and the user would press 'Enter' to go through the sequence.

```
d.identifyMotors();
```

This function checks if a specific motor possesses information that is queued (or registered, on the control table).

```
if (d.isQueued(motor_number)) ...
```

4.1.5 Manual Adjustments

For advanced users who seek manual access to the control table, functions to read, write and queue data to the control table are provided. These functions require knowledge of the control table and the corresponding limits and valid inputs, since there are no checking mechanisms introduced to these functions within the SDK.
Definitions:

- Byte: corresponds to the value within a single address

- Word: composed of two bytes (low and high), corresponds to two consecutive addresses, starting with the low byte. (Dynamixel SDK provides functions like

  ```
  int word = DXLObject.dxl_makeword(lowbyte, highbyte);
  int lowbyte = DXLObject.dxl_get_lowbyte(word);
  int highbyte = DXLObject.dxl_get_highbyte(word);
  ```

  which are useful for converting words to bytes and vice versa.)

- 2Word: composed of two words, or four bytes, corresponds to four consecutive addresses. This is specifically for controlling two settings, each corresponding to two bytes, and are located next to each other on the control table (e.g. speed and position). This function is provided for advanced users who wish to maximize communication efficiency.

(For the subsequent functions, `P_ADDRESS` and `P_ADDRESS_L` refer to the macro defined on `control_table_constants.h`. For words, `P_ADDRESS_L` is the address of the parameter's lower byte, which is also suffixed by an _L.)
Reading:

```
int byte = d.readByte(motor_number, P_ADDRESS);
int word = d.readWord(motor_number, P_ADDRESS_L);
```

Writing:

```
d.setByte(motor_number, P_ADDRESS, value);
d.setWord(motor_number, P_ADDRESS_L, value);
d.set2Word(motor_number, P_ADDRESS1_L, value1, value2);
```

Reading from All Motors:

```
// Bulk read implemented
vector<int> allBytes = d.readAllByte(P_ADDRESS);
vector<int> allWords = d.readAllWord(P_ADDRESS_L);
```

Writing to All Motors:

```
d.setAllByte(P_ADDRESS, vector_of_values);
d.setAllWord(P_ADDRESS_L, vector_of_values);
d.setAll2Word(P_ADDRESS1_L, vector_of_values1, vector_of_values2);
```

Queuing:

```
d.queueByte(motor_number, P_ADDRESS, value);
d.queueWord(motor_number, P_ADDRESS_L, value);
d.queue2Word(motor_number, P_ADDRESS1_L, value1, value2);
d.executeQueue(); // Write queued values
```

4.2 Controlling with DXMotorSystem

The `DXMotorSystem` class is the main class to use to control a sequence of motors connected to a single USB device.
A pointer to a `DXMotorSystem` object can be instantiated by

```
DXMotorSystem *d_pointer = new DXMotorSystem(int devicePort, int dxlBaudRate)
```

where `devicePort` refers to the serial number corresponding to the USB port (dev /.ttyUSB* where * is typically 0, 1, 2...) and `dxlBaudRate` refers to the data value corresponding to the desired baud rate (`DEFAULT_BAUDRATE`, which is typically 1 – 10 Mbps). The `DXMotorSystem` can access all the public functions of `DXSystem` as listed above, in addition to functions that control motor positions, speeds and torque controls.

4.2.1 Motor Motion Limit Settings

These functions are mainly to handle hard limits and settings for the motors.
Position Limits:

```
d.setPositionLimits(motor_number, lower_limit, upper_limit);
d.setAllPositionLimits(v_lower_limit, vector_upper_limit);
int lower_limit = d.getPositionLowerLimit(motor_number);
int upper_limit = d.getPositionUpperLimit(motor_number);
```

Home Position:
(For internal records to what 'default' positions should be. Upon initialization, the positions detected would be saved as home until the `setAllHomePosition` is called.)

```
d.setAllHomePosition(home_positions);
vector<int> homePosition = d.getAllHomePosition();
```

Torque Maximum Limit:

```
d.setTorqueMax(motor_number, upper_limit);
d.setAllTorqueMax(v_upper_limit);
int upper_limit = d.getTorqueMax(motor_number);
```

Torque Enable Settings:

```
d.setTorqueEn(motor_number, enable_boolean);
d.setAllTorqueEn(enable_boolean);
boolean enable = d.getTorqueEn(motor_number);
```

4.2.2 Position and Speed Control

The position and speed of motors can be controlled using the following functions.
Position:

```
d.setPosition(motor_number, goal_position);
d.movetoPosition(motor_number, goal_position); // set and wait until motor stops
d.queuePosition(motor_number, goal_position);
d.setAllPosition(v_goal_position);
int current_position = d.getCurrentPosition(motor_number);
vector<int> positions = d.getAllPosition();
```

Speed:

```
d.setSpeed(motor_number, goal_speed);
d.queueSpeed(motor_number, goal_speed);
d.setAllSpeed(v_goal_speed);
int current_speed = d.getCurrentSpeed(motor_number);
vector<int> current_speeds = d.getAllCurrentSpeed();
int current_set_speed = d.getSetSpeed(motor_number);
vector<int> set_speeds = d.getAllSetSpeed();
```

Other Functions

```
bool is_moving = d.isMoving(motor_number); // Motor is still moving
d.resetMovingSettings(motor_number); // Reset to 0 speed and 'home' position
d.resetAllMovingSettings(); // Reset all motors to 0 speed and 'home' position
```

4.2.3 Fine Motor Control through Compliance/PID Settings

The following setter and getter functions are for finer and more complex control of motor movements.
Punch (Current to drive motor):

```
d.setPunch(motor_number, value);
d.setAllPunch(v_values);
int punch_value = d.getPunch(motor_number);
```

For the MX-series motors, closed loop feedback using PID scheme can be achieved. The following functions can help facilitate the control of the PID loop.
PID:

```
d.setGainP(motor_number, p_value);
d.setAllGainP(v_p_values);
int p_value = d.getGainP(motor_number);
d.setGainI(motor_number, i_value);
d.setAllGainI(v_i_values);
int i_value = d.getGainI(motor_number);
d.setGainD(motor_number, d_value);
d.setAllGainD(v_d_values);
int d_value = d.getGainD(motor_number);
```

For other motors, compliance margins and slopes are used for flexible control of the motors.
Compliance Control:

```
d.setComplianceSlope(motor_number, cw_slope, ccw_slope);
d.setAllComplianceSlope(v_cw_slope, v_ccw_slope);
int cw_slope = d.getComplianceSlopeCW(motor_number);
int ccw_slope = d.getComplianceSlopeCCW(motor_number);
d.setComplianceMargin(motor_number, cw_margin, ccw_margin);
d.setAllComplianceMargin(v_cw_margin, v_ccw_margin);
int cw_margin = d.getComplianceMarginCW(motor_number);
int ccw_margin = d.getComplianceMarginCCW(motor_number);
```

4.3 Controlling with DXSingleMotor

`DXSingleMotor` is a subclass of `DXMotorSystem`, and hence inherits `DXMotorSystem` functions. The object can only hold a single motor within the system; otherwise, an exception is thrown.
A `DXSingleMotor` object can be instantiated by

```
DSingleMotor ds = new DSingleMotor(int devicePort, int dxlBaudRate)
```

As `DXSingleMotor` is a special case of `DXMotorSystem` with only 1 motor, some changes have been introduced to all the functions. Notably, all functions that are meant to write to ”all motors” are inaccessible. Additionally, all setter and getter functions no longer require the `motor_number`, as it is default to the value 0 for such a system (with only 1 motor). The definitions and purposes of the functions largely remain unchanged.
This class was designed with the intention of creating a complex module comprising a single motor and other components like sensors. An object class for such a module can be created by extending the `DXSingleMotor` class and include the functions for other sensors in use.

4.4 Setting up with `DXSetupMotor`

`DXSetupMotor` extends `DXSystem` as a class that aids in motor setup and reset. This class can only handle one motor at a time to prevent conflict in motor IDs. (When two motors with the same ID are connected, the behavior of the communication between the system and the motors becomes unpredictable.)
Motor setup can be done through instantiating a `DXSetupMotor` object by

```
DXMotorSetup dsetup = new DXMotorSetup(int newID, int devicePort, int dxlBaudRate)
```

where newID should be a unique number between 0 to 253 for each individual motor. The constructor resets the motor to factory settings before writing user-defined default settings to the motor. (Note: Some manual delays have been introduced within the reset function to prevent corruption in communication. As the setup should be done prior to and separate from the actual program, these delays should not affect the performance of execution when the whole system is connected.)

5 Sample Usage

5.1 File Organization

The files are organized as follows

- `dxllibclass` contains the modified Dynamixel SDK
- `dclass` contains all implementations of the new classes and additional resources
- `dtools` contains additional `cpp/h` files with functions that help with high-level tasks, e.g. parsing files, instantiating master/slave system and setting up the system.
- All new source files (including `main.cpp`) should be in the folder **`src`**. `userinputfn.cpp/.h` and `user_settings.h` allow users to change settings and behavior of the system.
- All CSV files will be read and written to the folder `data`.

5.2 Functions for Model-Related Data

Certain parameters, such as range of joint angles and position data or Compliance/PID capabilities, are model specific. To facilitate in encoding the specifications of different motor models, the functions within `dmodeldetails.cpp/.h` provides the information given a model number (corresponding to the value encoded in the EEPROM) as the argument. This parameter can be called from d.getModel(motorNum). As mentioned, new motor models may also be compatible as long as the control table is similar and this file is updated with the new specifications. The main functions are mentioned below.
To obtain the range of position values (minimum, maximum and middle positions):

```
int midPos = modelMiddlePosition(model);
int maxPos = modelMaxPosition(model);
int minPos = modelMinPosition(model); // generally 0
```

To obtain the angle range achievable in joint mode:

```
int angleRange = modelAngleRange(model);
```

To determine whether the motor is capable of PID/compliance settings and bulk-read:

```
bool bulkRead = bulkreadCapable(model);
bool pidMode = pidCapable(model);
bool complianceMode = complianceSettingCapable(model);
```

To determine the default baud rate upon factory reset (for `DXSetupMotor`):

```
int baudRate = modelDefaultBaudRate(model);
```

(The file also contains speed-related functions for respective models, but they were generally not used in most use cases.)

5.3 Additional Tools

Additional functions that may be useful when using the new library are defined in `additionaltools.cpp/.h`. To use these functions, include the header

```
#include "dtools/additionaltools.h"
```

There are six functions currently defined in the file, that may be useful when controlling the Dynamixel system and using the library.
Asking for inputs is common in many console-based interfaces. Two functions have been created to aid in parsing input stream.

```
int number = getInt(); // To get an integer
bool flag = getYorN(); // To get Y or N (boolean)
```

When parsing a text file, conversion of string (`std::string`) to integer numbers is required. Hence, the function `str2int` is also defined.

```
int number = str2int(string);
```

Delay functions are useful in imposing a fixed period in a loop or providing some latency within communication. The function `delay` takes in time duration in milliseconds, and will cause the current thread to sleep.

```
delay(time_in_milliseconds); // this thread sleeps
```

When writing to a filename, the use of timestamp would help users differentiate differnet files and also prevent files from being overwritten. The function `getTimeStr` provides a string with formatted time (inverse format, YYYYMMDDhhmmss)

```
string time_string = getTimeStr();
```

Lastly, with regards to exception handling, users can decide between throwing exceptions (and catching them to handle it) or simply print it to the console (`cerr`) without interrupting the program. This function should mainly be used for non-vital errors and exception. The function can be used by

```
string msg = "This␣is␣an␣error␣message";
throwPrintError(msg, throw_flag);
```

If the `throw_flag` is true, a `runtime_error` with an error message is thrown. Otherwise, the string is simply printed to the console and the program continues.

5.4 System Setup

A `DXMotorSystem` pointer can be instantiated using the pre-defined function

```
#include "dtools/setup.h"
...
DXMotorSystem* d_pointer = dxsystemSetup(devicePort); //devicePort = 0,1,2...
```

Alternatively, its object can be instantiated by de-referencing the pointer

```
DMotorSystem d = *dxsystemSetup(devicePort); //devicePort = 0,1,2...
```

Calling dxsystemSetup instantiates a DXMotorSystem object, writes user-defined default settings to all motors, performs some checks on the system and returns a pointer to the object.
The default settings used are set via the constants/macros defined in user_settings.h and instructions in the function dxlSetupEEPROM within `userinputfn.cpp` (found in `src` folder). These files may be modified to attain the desired default settings for the motors. Multiple DXMotorSystem pointers can also be instantiated using the function

```
#include "dtools/setup.h"
...
vector<DXMotorSystem*> all_d_pointers = multidxsystemSetup(num_of_ports);
// OR
vector<DXMotorSystem*> all_d_pointers = multidxsystemSetup(vector_of_port_nums);
```

This function instantiates multiple `DXMotorSystem`, using the device port numbers 0 to `num_of_ports-1` for the former case, or all the port numbers listed in the vector argument for the latter case.
The `setup.cpp/.h` also offers the function `dxlSetupSequence` which would aid in setting up the system prior to any use. This is particularly useful for newly built system, where the EEPROM settings have to be reset. This function prints the instructions on the terminal, of which the user should follow. The steps involve connecting the motors one at a time, so as to perform a factory reset, write the default configuration settings and assign a unique ID to the motor.

```
dxlSetupSequence();
// Instructions appear on terminal
```

5.5 Read/Parse CSV File with Joint Angle Data

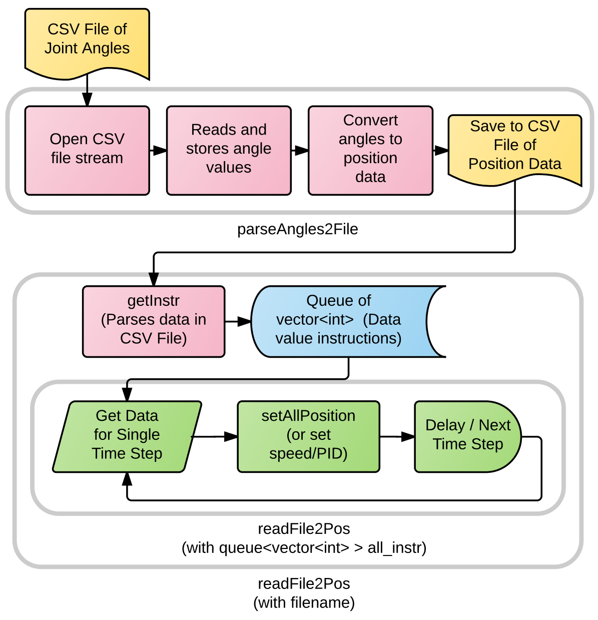

CSV File of Joint Angles
Open CSV file stream
Reads and stores angle values
Convert angles to position data
Save to CSV File of Position Data
parseAngles2File
getInstr (Parses data in CSV File)
Queue of vector<int> (Data value instructions)
Get Data for Single Time Step
setAllPosition (or set speed/PID)
Delay / Next Time Step
readFile2Pos (with queue<vector<int> > all_instr)
readFile2Pos (with filename)

Figure 2: Read Joint Angle File Scheme

The functions to read and parse CSV files can be found in `readfile.cpp/.h` in the folder `dtools`. All CSV files are read and written from the **data** folder. Names of the files written will be appended with the system date and time (to identify the files and to prevent overwriting). There are several functions that may be used, depending on the format of the data within the CSV file. To use these functions, the header file has to be included.

```
#include "dtools/readfile.h"
```

The first set of functions, `getDXSystemInfo` and `writeDXSystemInfo`, deals with model-dependent information (max position, angle range and max speed) for every motor in the `DXMotorSystem` object. The former, `getDXSystemInfo`, returns a vector with the relevant information for use in subsequent functions, while the latter, `writeDXSystemInfo`, writes the information in a CSV file (which may be subsequently used in other programs).

```
vector<Limits> allLimits = getDXSystemInfo(d); // obtains limits
string filename = writeDXSystemInfo(d); // returns filename of CSV file
```

To aid in setting of the system's 'Home' position, there are also two additional functions. These functions allow for the home position of the motors to be written or read from the homeFile

```
writeHomePositions(d, homeFile);
readHomePositions(d, homeFile);
// homeFile is an optional parameter, default to "data/homepositions.csv"
```

For the following functions, a CSV file can be read and parsed. The function `parseAngles2File` parses raw angles (encoded in degrees or radians) from a CSV file and converts them into digital position values for each of the motor, recorded within a new CSV file. The function also calls `getDXSystemInfo` within its definition, as the motor information is required for the conversion. The function also returns the name of the written file.

```
parseAngles2File(d, filename, hasLeftHeader, hasRightHeader, isRadians);
parseAngles2File(d, filename);
// default left/topheader true, isRadians false (i.e. degrees)
parseAngles2File(d); // default filename is "data/angles.csv"
```

The subsequent functions are able to write the corresponding data values from a CSV file to all motors at every time step. Between each time step, a delay is imposed so as to facilitate a smooth motion within the motor systems. This delay can defined and can either be system-dependent (e.g. until all motors

stop moving before proceeding) or time-based (e.g. delay for 10 ms). Delay behavior can be defined in the function `timepointDelay` in `src/userinputfn.cpp`.
Data to be written to the control table may be a single byte or a word (two bytes, consisting of a low and high byte). Hence, the functions `readFile2Byte` and `readFile2Word` are given, depending on what kind of attributes the data represent. (E.g. Speed and Position are words while PID gains are 3 individual bytes.) There are two ways that these functions may be used.
The first method is directly passing in the CSV files as parameters.

```
readFile2Byte(d, filename, delayTime);
readFile2Word(d, filename, delayTime);
```

The parameter delayTime is optional, and is set at 4 ms if no value is given.
The second method is parsing the file into a 2D vector prior to parsing the information.

```
queue<vector<int> > all_instr;
getInstructions(all_instr, filename);

readFile2Byte(d, all_instr, delayTime);
readFile2Word(d, all_instr, delayTime);
```

The second method is useful if the readFile functions are used in a loop, but the file remains unchanged (i.e. avoiding opening the file and parsing it multiple times).
Special versions of the readFile have also been defined for parsing, position values only, position/speed values and position/speed/PID gain values. However, the template of these CSV file have to comply with requirements.
The use of these functions are largely the same as above.

```
readFile2Pos(d, filename, delayTime);
readFile2PosSpd(d, filename, delayTime);
readFile2PosSpdPID(d, filename, delayTime);
```

```
queue<vector<int> > all_instr;
getInstructions(all_instr, filename);

readFile2Pos(d, all_instr, delayTime);
readFile2PosSpd(d, all_instr, delayTime);
readFile2PosSpdPID(d, all_instr, delayTime);
```

(There are also other optional parameters that can be passed as arguments. E.g. the booleans `hasTopHeader` and `hasLeftHeader` are used in conjunction with `filename`, depending on the presence of headers in the CSV file; another argument, `runFlag`, is a reference to a boolean variable that can be subsequently used for threading. This allows for the read functions to stop in the middle of a file by setting the `runFlag` to false, thereby prematurely terminating the function.)
Lastly, a helper function to loop through the instructions from a CSV file is also provided.

```
loopReading(d, allInstr, runFlag, delayTime, loop);
```

In this case, the function `getInstructions` should be called first, to minimize the need for opening and parsing the same file at every iteration. The boolean variables `runFlag` and `loop` determines whether the file-reading scheme should be looped (`runFlag` is a reference to a boolean variable, as described above; `loop` is a boolean variable that indicates if the function should only perform the file-reading scheme once or in a loop, and is default to `true`).

5.5.1 With Multiple Ports

To facilitate communication with multiple devices at once, multiple ports may be used. This is made possible with the changes introduced to the modified SDK. Subsequently, multi-threading should be adopted to seamlessly control multiple systems simultaneously.
The use of multiple ports is crucial to the bilateral control scheme, and is also used in threaded reading (feedback loop control) scheme.

5.6 Feedback Loop

Another way of controlling the motors is through a closed feedback loop. In this scheme, the desired position (and speed) for the motors at the next timestep is calculated based on the previous/current state (and sensor readings, if any). The transfer function utilized for this loop is defined under `calcNewPosFromFile` in `src/userinputfn.cpp`, which can be modified to suit the project demands (more details below). Demonstration of the feedback loop is combined with the multi-threading sequence samples.

5.6.1 Multi-Threading

Multi-threading allows for functions to be run in parallel. The C++11 `std::thread` is adopted as it is simpler to use and independent of operating system. Sample sequences involving threading are demonstrated in `threadedreadfile.cpp/.h`. These functions may be adopted and modified as a template or used as-is (by including "dtools/threadedreadfile.h"), depending on the demands of the program.

5.6.2 Cautionary Note on Multi-Threading

Unlike sequential programming, parallel computing may result in concurrency issues. One of the most common pitfalls is the concurrent access (and modification) of variables and objects. When multi-threading is in use, potential concurrency issues should be taken into consideration.

5.6.3 Between Communication and Calculation

Another place where threading may be introduced is the data communication and calculation. To facilitate parallel computing, computation and communication for each individual port can each be run on a separate thread (assuming they do not require access to the same variables all at once).
In this specific sequence, a "one-ahead" calculation scheme is used. The desired goal positions are communicated to each port on separate threads, while the calculated goal positions for the next time points are based on the positions of the previous time point. This minimizes the waiting time, and hence the execution time for each loop.

5.6.4 Read File and Feedback Loop

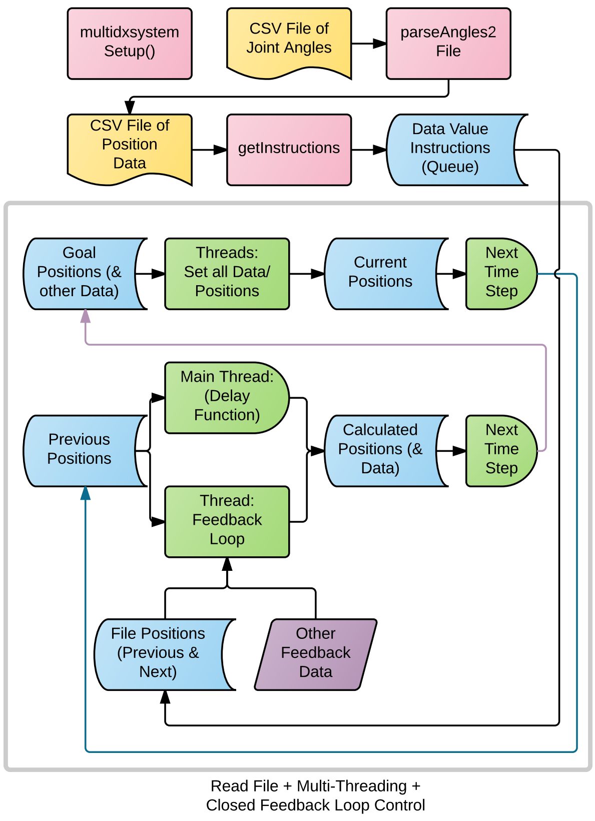

multidxsystem Setup()
CSV File of Joint Angles
parseAngles2 File
CSV File of Position Data
getInstructions
Data Value Instructions (Queue)
Goal Positions (& other Data)
Threads: Set all Data/ Positions
Current Positions
Next Time Step
Main Thread: (Delay Function)
Previous Positions
Calculated Positions (& Data)
Next Time Step
Thread: Feedback Loop
File Positions (Previous & Next)
Other Feedback Data
Read File + Multi-Threading + Closed Feedback Loop Control

Figure 3: Threaded File Reading and Feedback Loop

To use the sequence as is, the following may be used

```
#include "dtools/threadedreadfile.h"
...
threadedReadFileSequenceSample(numPorts, filename, runFlag, delayTime);
// runFlag is a reference to boolean variable, described above
```

In this function, multiple ports can be used, but the CSV file should contain instructions for the sum of all motors connected. (E.g. if port 0 contains 6 motors and port 1 contains 5 motors, the CSV file should have 11 columns of data, where the first 6 corresponds to motors on port 0 and the last 5 corresponds to motors on port 1.)

5.7 Bilateral Control using Master/Slave System

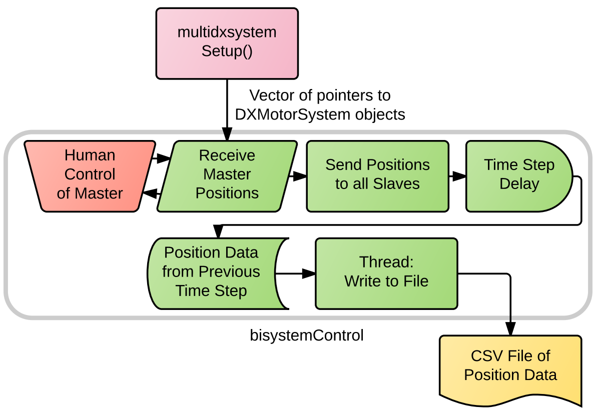

multidxsystem Setup()
Vector of pointers to DXMotorSystem objects
Human Control of Master
Receive Master Positions
Send Positions to all Slaves
Time Step Delay
Position Data from Previous Time Step
Thread: Write to File
bisystemControl
CSV File of Position Data

Figure 4: Bilateral Control through a kinesthetic master/slave system interface

Through the implementation of multiple serial devices, we can connect 2 (or more systems) and control them simultaneously through a 'master' system. The systems should be initialized before calling the bilateral control function.

```
vector<DXMotorSystem*> allSys = multidxsystemSetup(numPorts);
// or multidxsystemSetup(vector_of_portnumbers);
bisystemControl(allSys, runFlag, goalTorqueSetting, filename);
// runFlag is a reference to boolean variable, described above
// goalTorqueSetting is a reference to an integer mode,
// 0 for no torque, 1 for low torque, 2 for high torque
```

Note that `runFlag` and `goalTorqueSetting` are reference to variables, to allow for changes in value that would subsequently modify the behavior accordingly (e.g. `runFlag` to loop/terminate the function and `goalTorqueSetting` to govern the torque settings on the master).

5.8 Programming by Demonstration through Bilateral Control/File Reading

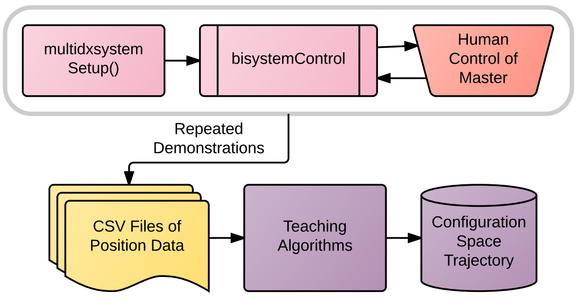


Figure 5: Programming by demonstration using a master/slave system, based on the bilateral control and file reading schemes

Noting that the bilateral control scheme generates a CSV file of the position data from a single run, the file can subsequently be read through the file reading scheme, thereby replicating the motion. Hence, by first using bilateral control to demonstrate ("teach") a trajectory, the motion can be replicated. This is a naiive implementation of programming by demonstration which may be adopted.
By repeated demonstrations using bilateral control, the collection of CSV files can subsequently be used as the basis for more complex teaching algorithms, calculating a robust trajectory for the system that can be read.

6 Graphical User Interface

The library also includes a graphical user interface (GUI) for high-level control features, specifically the file-reading and bilateral master/slave control capabilities. The code uses the Qt framework, and can be compiled in Qt Creator IDE.
The provision of these GUI allows for quick and simple solution to controlling motor systems, particularly at preliminary stages of prototyping. The two main schemes provided are file-reading and bilateral control. While a feedback loop interface is provided, further coding of the closed loop behavior (`calcNewPosFromFile`) is required.

6.1 Main Window

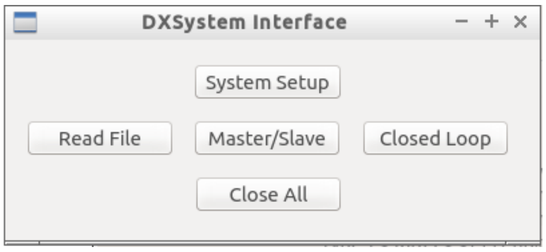
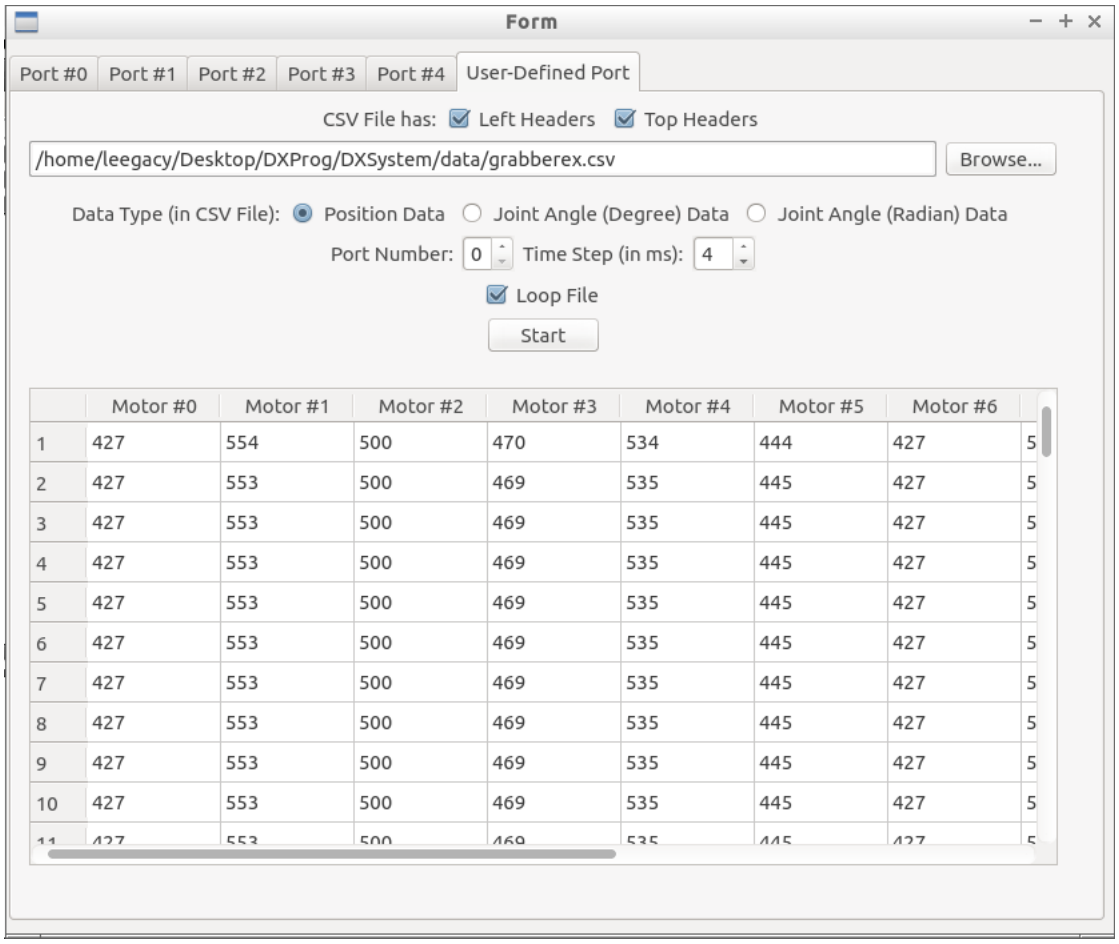


Figure 6: GUI Main Window

The main window for the GUI consists of five toggle buttons. It is recommended to use the terminal alongside the GUI, as the console provides status or error messages relating to the system.
The five buttons are exclusive, meaning that only one mode can be used at any one point in time. This is to minimize the potential issues arising from potential conflict between programs and between instructions to the same serial port.
The mode “System Setup” is a sequence to set up the motors (described in the section above). The instructions will appear on the terminal.
The three modes, “Read File”, “Master/Slave” and “Closed Loop”, will be discussed in detail below.
The “Close All” button will close the active window for the three modes.

6.2 Read File



CSV File has: [✓ Left Headers] [✓ Top Headers]

/home/leegacy/Desktop/DXProg/DXSystem/data/grabberex.csv

Data Type (in CSV File): [✓ Position Data] Joint Angle (Degree) Data Joint Angle (Radian) Data

Port Number: 0 Time Step (in ms): 4

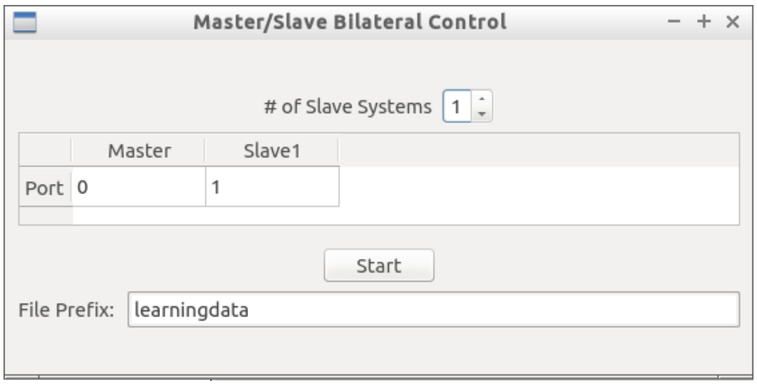
[✓ Loop File]

	Motor #0	Motor #1	Motor #2	Motor #3	Motor #4	Motor #5	Motor #6	
1	427	554	500	470	534	444	427	5
2	427	553	500	469	535	445	427	5
3	427	553	500	469	535	445	427	5
4	427	553	500	469	535	445	427	5
5	427	553	500	469	535	445	427	5
6	427	553	500	469	535	445	427	5
7	427	553	500	469	535	445	427	5
8	427	553	500	469	535	445	427	5
9	427	553	500	469	535	445	427	5
10	427	553	500	469	535	445	427	5
11	427	553	500	469	535	445	427	5

Figure 7: GUI for File Reading Scheme

The file reading GUI is a tabbed interface, to allow for control of multiple devices on different ports within the same window. The ports 0 to 4 are offered, while a user-defined port tab is given for better customization.
Using the “Browse...” button, the CSV file can be obtained, and the data will be reflected in the table. The checkboxes, “Left Headers” and “Top Headers”, and radio buttons, “Position Data”, “Joint Angle (Degree) Data” and “Joint Angle (Radian) Data”, aid to identify the format of the file.
The time step box dictates the time step per row of values, while the checkbox “Loop File” dictates if the system should repeat the motion or only perform it once. (“Loop File” should only be used if the first and last rows are not too different.)
At this moment, the file reading GUI is limited to file-to-position scheme.

6.3 Bilateral Control



# of Slave Systems: 1

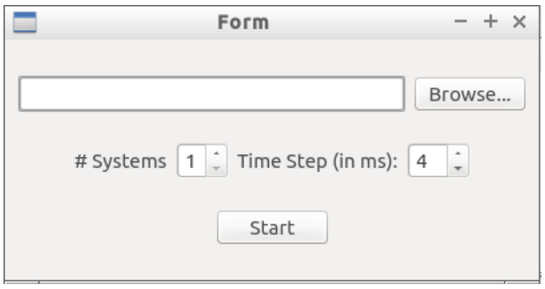
	Master	Slave1
Port	0	1

File Prefix: learningdata

Figure 8: GUI for Bilateral Control of Master/Slave System

The bilteral control GUI is a simple interface, only requiring number of slave systems, the respective port numbers for the master and slaves, and a file prefix for writing the CSV file. Pressing the “Start” button will initiate the bilteral control interface, and the slave systems will replicate the motion of the master system (by the user).

6.4 Feedback Loop (Preliminary interface)



Systems: 1 Time Step (in ms): 4

Figure 9: Preliminary GUI for Threaded Read/Feedback Loop

The current Feedback Loop GUI is a preliminary interface with a naiive implementation. It is not too different from a typical file reading scheme, with the exception that a single file can be used to control multiple systems (more details discussed in the section on threaded reading/feedback loop above).

7 Known Issues within DXSystem

1. Rapid consecutive reading of bytes/words lead to packet corruption or timeout when receiving (`RXCORRUPT` or `RXTIMEOUT`). – The cause is believed to be poor electronic connection, resulting in lost or corrupted packets at high speeds. Further testing is required to identify and fix the issue.

2. When executing the program, the folder **data** must be in the same directory as the binary file (program file). The `ifstream` is unable to open the file if this condition is not met. – Current workaroud is to place the binary file together beside the **data** folder, or to change the execution path to where the **data** folder is.

3. The current implementation is not robust against opening the same port multiple times.

8 DStopWatch

The class, DStopWatch, is a new class created to characterize execution time. Each DStopWatch instance corresponds to an individual stopwatch. It can be used as follows

```
DStopWatch dsw; // Initialize object
dsw.start(); // Start stopwatch
long long timeLap = dsw.lap(); // Lap, record time
...
long long timeElapsed = dsw.stop(); // Stop, record time
```

(`int` can be used instead of `long long` if the time elapsed is not a huge integer.)
The time returned is in nanoseconds (through the use of a high resolution clock from C++11 `chrono` package). However, the practical resolution of the clock is dependent on the system.

8.1 Characterizing Dynamixel SDK Functions

Using the stopwatch object, the execution time of some basic functions of the new dynamixel SDK were characterized. In summary (and as a rough guide),

- Writing bytes (to a single or all motors) takes about 5-6 μs. (Time taken scales with number of bytes to write, but not with number of motors.)
- Reading an address off a motor takes about 1 ms. (Cumulative time for multiple MX motors is reduced through the use of `BULK_READ`.)

These are based on the execution time of the code, and does not take into account mechanical/circuit latencies or communication delays (different system delay times, as per settings on control table).