MCUnity SDD

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| MCUnity application Software Design Document | 05/09/2016 |

# MAJOR DESIGN ISSUES

## Re-Setup Request

When the app crashes and restarts, it doesn’t know where the MCU’s are. It does its broadcast but no MCU will reply to it any longer (this only happens once). So there’s no way for the application to know which IP addresses to send a Re-Setup Request.

SOLUTION: make that request a broadcast. Unlike the initial broadcast, it should be non-recurring.

I can’t just make the initial broadcast non-recurring : the MCU needs to behave differently when it connects to the app the first time and when a re-setup is requested, especially if there are different MCU’s connecting to the app at different times (after and before the app’s crash / restart)

# IDEAS TO TURN INTO SPECS

## Support for Multiple Simultaneous ESP’s

The idea is to also associate their IP address to each tile.

In terms of layout, things can get complicated. Perhaps a tabbed screen is the best approach?

I could also imagine a system where the user can rearrange tiles to get the combination of “views” he needs.

# Abstract / Project Summary

MCUnity is a firmware development tool. It’s essentially the combination of a Unity application and a library for an MCU that provides a nice user interface with the following capabilities:

* Accessing global variables and ESP registers
* Launching tasks, calling functions
* Displaying text from ESP to Unity

The Unity application is generic, i.e. not tailor-made for a specific microcontroller family or firmware project. Its GUI is configured at run time and from the firmware. This keeps the user focused on MCU firmware development.

## Modular Design

Designing and programming MCUnity requires working simultaneously on two different fronts:

* Unity development in C#
* MCU development in C/C++

This requires two different sets of tools.

To help deal with the complexity, MCUnity is designed to be very modular. This document both describes how the existing features of MCUnity are implemented and how to add new ones.

This modularity also makes it easier to offer **frequent updates**.

# System Architecture

An MCUnity system is a set of:

* One computer running the MCUnity application
* One or more microcontrollers (MCU) running firmware using the MCUnity library

MCU do not communicate with each other as part of the MCUnity system, although they may communicate with each other for unrelated purposes. Therefore, the MCUnity system has a **star topology**. To keep this document simple, the author assumes there’s only one MCU in the system, unless otherwise specified.

## Unity Application

The Unity application is intended to be completely generic, meaning it should not need to be modified to suit a particular type of MCU or a particular MCU firmware project. The application should be seen as a monolithic tool to be controlled from an MCU.

This requirement has crucial aims:

* Limit MCUnity system development to MCU programming only.
* Remove the need for installing / reinstalling multiple variants of the Unity application.

## MCU Library

MCUnity is a software debugging tool, although it may also be used to provide a remote GUI to an MCU. In either case, it is required for the MCU firmware to use the MCUnity library to perform the following tasks:

* Establish connection with the Unity application
* Setup the Unity application’s GUI
* Respond to GUI commands
* Update the GUI contents

The MCUnity library is designed so that it can be built optionally into a firmware project. This means it can be excluded from release builds. Given its size and RAM utilization, but also the fact that it is technically a network backdoor, it is recommended to exclude the MCUnity library from any firmware release. **Because of its polymorphism and intended purpose, MCUnity is neither an optimized GUI system nor a secure GUI system**.

### Target Hardware and System Requirements

MCUnity is primarily designed for 32-bit microcontrollers.

MCUnity requires a local network connection to the machine that runs the Unity application. That can be either a WiFi or Ethernet connection.

MCUnity relies on the lwIP network stack.

CPU performance and memory requirements **TBD**.

# Terminology

Unless otherwise specified:

**Application** describes the MCUnity Unity application. The application is programmed in **C#**.

**Firmware** describes the firmware running on the MCU. The MCUnity library for the firmware is programmed in **C**.

**Opcode** (operation code) describes a unique 8-bit operation identifier.

**Operation** describes an MCUnity operation where the firmware sends a command to the application or the application sends a command to the firmware.

**Packet** describes the payload of a UDP packet sent between the application and the firmware on the MCUnity port (55555, or “five fives”).

**Payload** is synonymous for **packet**, as defined above.

# Network Protocol

MCUnity uses UDP, with port 55555 (five fives).

In keeping with the choice of UDP, which is connectionless, the MCUnity protocol is based entirely on single packets.

MCUnity UDP transfers are strictly **point to point** except for one situation: mutual discovery. Initially, the application and the firmware don’t know each other’s IP address. The application periodically sends a UDP broadcast packet on the MCUnity port which will be received by any MCU on the LAN that is running the MCUnity library. This will let the MCU know the IP address of the machine that runs the application. From then on, what logically follows is a phase where the MCU firmware will setup at least one GUI element, requiring transmission of one UDP packet to the application. Upon receiving that packet, the application will know the IP address of the MCU.

For the purposes of this document, the terms “packet” and “payload” are interchangeable and both refer to the payload of a UDP packet sent between the application and the firmware on the MCUnity port.

All packets start with a single-byte opcode. The format of the rest of the packet is inherent to the opcode.

A packet may contain at most one variable-length field, which must always be the last field in the packet. This is to eliminate the need to generate, transmit and decode field-length fields.

## Operation Sets

For a given variable type there are up to four possible packets / operations. Opcodes are selected so that their first six bits are identical for a given variable type. The two least significant bit are always the same for an operation type:

* 00 - Setup: the firmware registers a variable of the type with MCUnity
* 01 - Set: the app sends a new value for a variable of the type
* 10 - Update: the firmware updates all variables of the type
* 11 - Request: the app requests an Update (see above)

# MCUnity Operations

An “operation” is a transaction between the MCU and the Unity application. It takes the form of a function call on the transmitting side, resulting in transmission of a single UDP packet, which triggers a specific response on the receiving side.

Other Side  
(Firmware or Application)

Operation Initiator  
(Application or Firmware)

One UDP packet

An operation is initiated by calling a dedicated **function** (in C) or **method** (in C#).

The application uses a thread to process incoming UDP packets. This thread parses the packet to determine the operation code (or opcode) and then passes on the packet to the relevant method.

The firmware uses an lwIP callback to process incoming UDP packets. Ideally, this callback should not call other functions.

Therefore, implementing an MCUnity operation takes the following steps:

* Protocol extension:
  + Assign a unique 8-bit operation code, or opcode, to the operation
  + Define its UDP packet’s payload format
* Implementation of the function (firmware) or method (application).
* Implementation of the parser method (application) or callback code block (firmware).

The protocol is described both in this document and in a spreadsheet stored with this document.

This section documents each supported operation ranked by rising opcode. In the following subsection titles those are indicated in the form “Ixxx” where “I” denotes the initiator (A for Application, F for Firmware) and “xxx” is an integer in the range 1 to 255.

## (F000) Setup Firmware Function

MCUnity provides the ability to trigger calls to firmware functions from the MCUnity application.

This requires the firmware to setup the function with a call to “**unity\_setup\_function**”. This function takes two arguments:

* A pointer to a function (the function’s name)
* A string that will be used by the application as that function’s “display name”

Note that currently the only firmware functions that can be call from the application’s GUI are those who take no argument and return nothing. The current implementation of the application shows them on the GUI as a button labeled with the display name provided by the firmware.

A good use for this feature is to write short firmware functions specifically for the purpose of debugging and making them “launchable” from the GUI.

## (A001) Application Broadcast

Purpose: periodic broadcast intended to let the firmware discover the IP address of the machine running the application.

Note: the broadcast is set to repeat at 1 Hz, which is considered a good compromise between network load and system responsiveness. Unlike all other packets sent by the application, the broadcast is send from a dedicated thread: future versions of the application may implement a feature to turn it off or activate it on user command.

Upon receiving this packet, the firmware saves its source IP address and transitions from mode “init” to mode “setup”. If the broadcast packet is received while the firmware is not in mode “init”, no state transition occurs.

Firmware variables that are modified:

* unity\_IP IP address of the machine running the MCUnity application
* unity\_mode MCUnity system state (firmware copy)

## (A002) Force Setup

Purpose: in case the application exits and restarts while the firmware is still running, causes the firmware to perform its setup operations again.

This also causes the firmware to transition from “update” mode back to “setup” mode while this operation is performed. This feature may be useful if the sequence of setup operations can be interrupted by FreeRTOS and another part of the firmware attempts to update the remote GUI.

## (A003) Call a Firmware Function

This operation causes the firmware to call a function that was previously registered with MCUnity (see operation F000).

On the application side, trigger a call to the firmware function by calling the method “**firmware\_function\_call**”. It takes as argument a firmware function number. Firmware functions are numbered from zero in the order they were setup by the firmware.

## (F004) Setup “int” Type Variable

Setup functions are used by the firmware to add controls to the GUI generated by the application.

This specific operation provides the application with the parameters for setting up a GUI control for an “int” variable (signed 32-bit integer):

* The variable’s unique index, which allows the application and the firmware to refer to the same variable without using its name or address.
* The variable’s current value, which the application will use to initialize the control.
* Minimum and maximum values that serve two distinct purposes:
  + They bind user input to a range that is compatible with the firmware.
  + They can help define the appearance of the GUI control or its operation, for example if the variable is set to be displayed as a percentage or a progress bar.
* A 32-bit “options” field to define the appearance of the GUI control and/or its modes of operation.
* The variable’s “display name”, a character string the application will use to label the control. It doesn’t need to match the variable’s name and can contain any ASCII character including spaces.

The unique index is generated by the MCUnity library, which also reads the “int” variable’s current value. The remaining fields are passed as arguments to the MCUnity firmware function that initiates this operation:

int unity\_setup\_int (int\* variable, const char\* name, int min, int max, uint32\_t flags);

Implementation note: each firmware variable type has a dedicated trio of operations:

* “Setup” on the firmware side, registers a variable with the MCUnit library and sends a command to the application to create the matching GUI control.
* “Set” on the application side, sends a new value to be assigned to a variable.
* “Update” on the firmware side, sends the value of one or several or all variables of the type to the application, so it can update the GUI.

### Application Side

DEVELOPMENT IN PROGRESS

Upon receiving an F004 packet the application stores all the parameters sent by the firmware and generates a GUI control from that information.

The current implementation is for development purposes only: I displays the variable’s name and value and allows for setting a new value.

Future implementation will allow the firmware to specify the appearance and features of the GUI element for a specific variable.

## (A005) Set “int” Type Variable

Purpose: this operation allows the application to set the value of an “int” variable in the firmware.

“Set” operations are used by the application to set the value of a variable in the firmware. In this case the variable to be set is of type “int” (32-bit signed). The packet contains the opcode (0x05), the unique index of the variable, and its value on 32 bits.

Implementation note: due to the fact that each variable type has its own “Setup”, “Set”, “Update” and “Request” operations, the unique index of a variable only needs to be unique among variables of the same type.

### Application Side

IN PROGRESS, IMPROVE INTEGRATION

In addition to the setup parameters send by the MCU to application in order to setup a GUI element for an “int” type variable, the application also stores a string that can be used as part of writing Unity GUI code to input a value.

This string is stored in an array named “**int\_user\_input**”.

GUI code for a button to send the value stored in that string to the firmware must call the method “**set\_int**” which takes a variable’s index as its argument. This method will attempt to parse the relevant element of “**int\_user\_input**” into an “int” and, if successful, will build a “set int” operation packet and send it to the firmware.

### Firmware Side

The incoming packet parser extracts index and value from the packet and stores the value in the relevant variable. This code is so short it’s not written as a function.

## (F006) Update “int” Type Variables

TO DO – CLARIFY DOCUMENTATION

Purpose: sends the current value of at least one registered “int” type variable to the application to update the GUI.

The only way for the application to update its display of firmware variables with their current values is if the MCU sends updated values of those variables to the application. This MCUnity operation takes care of that.

The operation is triggered by calling “unity\_update\_int (int offset, int count);” where “offset” is the unique index of the first variable to update and “count” is the number of variables to be updated. If both parameters are zero, all variables will be sent. If only “count” is zero, all variables starting from “offset” will be sent.

Basically, it should be called:

* Whenever one or several variables firmware have changed.
* No more often that is sensible, considering the refresh rate of a typical GUI and what the user’s eyes can follow. Calling this function too often will overload the network.

Note that this operation can actually be triggered from the application using the next operation (Request Update). This means that in some cases it may not be necessary for the firmware developer to take care of placing Update operations in his code.

The Update operation sends the value of one or several “int” type variables. The packet starts with the unique index of the first variable to be updated. Then come one or several 4-byte “int” values. An update packet can thus update the value of one variable or of several consecutive variables. The number of variables to be updated is inherent (it is determined based on the size of the packet)

Keep in mind that variable unique indices are assigned based on the order in which the relevant setup operations were performed. The first variable setup is therefore “0”, followed by “1”, and so on. To make the best use of the Update operation it is therefore a good practice to setup variables in a sequence that makes sense, such as grouping together all variables dealing with a specific functionality of the firmware being debugged.

It remains possible to send individual variables, of course, but sending them packed reduces network load and lets you increase the update rate as a result.

The same doesn’t apply in the other direction (A005) because it is assumed a human user of the GUI cannot update more than one variable at a time, or within the time it takes the application to build and transmit a packet. There’s therefore no need to send multiple variables updates in a single packet.

## (A007) Request “int” Update

IMPLEMENTED BUT NOT TESTED YET

This operation lets the application request the firmware perform operation F006: Update “int” Type Variables (see above). This can be used to let the Application determine when or how often the firmware should send the value of “int” variables.

Note that this causes the firmware to send the current value of **all** “int” variables registered with MCUnity, which may not be efficient.

Application-side, call the method “request\_int” (no argument, no return value) to perform this operation.

## (F008) Setup MCU Display Name

NOT IMPLEMENTED YET

This operation lets the MCU tell the app which name to display as the MCU’s name. This is only important if multiple MCU’s are connecting to the app. Note that display names don’t need to be unique: the app differentiates between MCU’s primarily through their IP address.

# Packet Field Formats

## GUI Control Options Field

This is a 32-bit field present in all “setup” operation packets. It sets the appearance of a GUI control:

* Bits 31...28: location – column
* Bits 27...24: location – row
* Bits 23...20: size – width
* Bits 19...16: size – height
* Bits 15...12: color 1
* Bits 11...8: color 2
* Bits 7…0: <reserved>

Notice that first four fields mimic the parameters of Unity’s “Rect” object, which will be used to display a GUI control.

### Basics of GUI Layout

The design of MCUnity makes no assumption as to the display size and definition of the machine that runs the MCUnity application.

This means screen coordinates and graphical object sizes must be expressed as **fractions** of the display’s definition.

To keep things simple yet provide the tools for flexible GUI design, MCUnity assigns one display “page” to each MCU connected to the application.

That page is organized as a grid of 16 x 16. Rectangular blocks on that grid form a tile. Each tile corresponds to a single element setup by the MCU. In other words, each MCUnity setup function call on the MCU translates to a single GUI tile.

(Note that it is possible for the MCU to setup several tiles doing the exact same thing).

Tiles can be as small as 1 x 1 grid units, which means an MCU can setup as many as 256 GUI tiles or controls. It is expected no firmware debug task requiring the use of MCUnity will require a more complex GUI.

### Tile Specification in Firmware

Since a tile’s appearance is encoded as 4-bit values packed into a single 32-bit field, it isn’t very practical to specify when writing GUI code for the MCU.

To that end, use the precompiler macro “GUI\_FLAGS” to create the appropriate constants, for example:

#define GUI1 GUI\_FLAGS(1,2,3,4,5,6,7)

Defines a 32-bit constant “GUI1” which represents a tile located in column 1, row 2, sized 3 x 4 grid array units, with colors 5 and 6, and the reserved sub-field set to 7. This constant can be passed as the “flags” argument to any MCUnity setup function.

# Firmware global variables

## GUI Setup Storage

## Network State

# Application data members (or fields ? see C# doc)

## GUI Setup Storage

MCUnity essentially provides GUI controls to variables and functions of firmware running on one or several networked MCU’s.

In its current version, MCUnity supports only one MCU connected at any time.

MCUnity stores various data pertaining to each GUI control setup by an MCU. That data can be divided into:

* Tile layout information, which is not specific to each tile’s type or the type of firmware data they represent.
* Type-specific information, for example “int” type firmware variables have their last known values stored in an array of “int” type variables.

### tile[] array

MCUnity defines the GUI\_Tile class to store tile data. Its contents can be defined for any type of tile:

* “name” is a string that is used as the tile’s label. Typically it’ll be a firmware variable’s name.
* “x”, “y”, “w”, “h”, “c1”, “c2”, “reserved” are the unpacked values passed by the firmware to MCUnity to define the look of the tile: position, size, colors and flags reserved for future use.
* “t” is the tile’s type. This typically depends on type of the firmware variable attached to the tile, and dictates how MCUnity renders the tile.
* “i” is the index of that variable in MCUnity’s type-specific storage arrays. It’s also the index the firmware attaches the to the variable for that tile. This is the link that allows GUI controls to impact the correct firmware variable and vice-versa.

### tiles

This integer is the number of tiles currently in use. Any time the firmware performs a tile setup operation it increases by one. When the application performs a setup request operation to the firmware, it also resets this variable, effectively erasing the GUI.

### “function” data storage

The setup operation for a function sends the application a “display name” for that function, which the application uses to draw a GUI button. Clicking that button sends a packet to the firmware telling it to call the function. Behind the scenes, the firmware does that by storing a pointer to the function and an index to match it to the GUI button.

Because tile[] array can store a name string and the tile’s appearance parameters, all that’s needed is a variable to keep track of how many firmware functions have been setup as GUI buttons.

#### firmware\_function\_occupancy

This is the number of “firmware function” tiles currently setup by the firmware.

Note: at present time MCUnity can only call functions with no arguments and no return value. To work around this, use global variables and setup GUI controls for them.

### “int” type tile data storage

The setup operation for an “int” type variable (signed 32-bit integer) passes along information the application can use to create a GUI control. That control lets the user read and set the variable’s value. This facility only works with global variables of the firmware.

#### int\_variable\_occupancy

This is the number of “int” tiles currently setup by the firmware.

#### int\_variable\_value[]

This array stores the last known value of each “int” variable for which the firmware has setup a tile. These values are updated by the firmware either on its own or at the request of the application (a feature that isn’t used at the moment)

#### int\_variable\_min\_val[] and int\_variable\_max\_val[]

These arrays store the minimum and maximum value that each “int” tile variable can be set to. (this feature is not currently used)

#### int\_user\_input[]

This array is used internally by the application for the input fields associated with each “int” tile. It allows for these input fields to be persistent.

## Network State

# Support for Multiple MCU

PRELIMINARY: USE TABS

*Also, simply add a dimension to all arrays used to store GUI setup information, that index identifying the MCU. MCU indices can be derived from the last byte of their IP address (on a LAN) going through a LUT to keep the arrays at a reasonable size on mobile devices.*

# GUI Design Fundamentals

MCUnity uses a **tile paradigm** for GUI design. The area of the display that can be customized from the firmware is divided into a grid of 16 x 16 **cells**. A tile can be located anywhere on that grid and have any size as long it is rectangular and does not exceed the grid’s boundaries.

The choice of a 16 x 16 grid ensures that tiles of 1 x 1 cell are readable on displays with resolutions of 720p and above. On displays with smaller resolution, larger cells will need to be used. MCUnity adapts its font size to the height of each tile, therefore:

* If a tile is unreadable, increase that tile’s height.
* If a tile’s content overflows onto the next tile, make the overflowing tile wider.

# Firmware Design with MCUnity

This may need to go into some sort of user / developer guide.

Here are the rules and best practices for integrating MCUnity into a firmware design.

## Location

In order to keep firmware source code clean and make it easy to exclude MCUnity calls from compilation, MCUnity should be integrated only in the firmware’s main source file.

## Include the MCUnity Header File

Add this statement to your firmware’s main source file:

#include “unity.h”

## Declare Global Variables

MCUnity is designed to allow access to a firmware’s global variables from a remote Unity application through a local network. It therefore requires global variables.

If possible, make the firmware’s “variables of interest” global.

## Write a GUI Setup Function

This function must take no argument and have no return value, i.e. its prototype should be in the form:

void gui\_setup\_function (void);

This function must contain the complete sequence of the firmware’s calls to individual MCUnity setup functions, and nothing else. This call sequence can be seen as the specification of the GUI that the MCUnity application will generate and maintain for the firmware.

A pointer to this function will be passed to MCUnity using the “unity\_init” function. This is to allow the remote Unity application to request the firmware execute its MCUnity setup sequence again. That is useful if the application is restarted while the firmware is running.

Centralizing GUI initialization also help development by making it easy to exclude MCUnity calls from compilation. It also makes it easy to maintain several different GUI setup sequences, to be used for investigating different aspects of the firmware’s operation.

This function must **never** be called directly by the firmware.

## MCUnity Initialization

MCUnity should be initialized as soon as possible **after** the firmware establishes a connection to the local network and acquires an IP address.

This is done by calling the “unity\_init” function (no return value).

“unity\_init” takes one argument: a pointer to the GUI setup function (see previous section).

It also sets up the network socket that will be used by MCUnity to communicate with the remote application.

## Wait for MCUnity to Connect

The MCUnity application will periodically (1 Hz) send a broadcast packet to let the firmware learn its IP address. Until the firmware receives and processes this broadcast message, all other MCUnity functions will not work.

To determine the current state of the connection between the application and the firmware, use the dedicated “unity\_not\_ready” function (no argument) which returns 1 until the connection is established, then 0.

The exact implementation of the wait loop is firmware-specific. For FreeRTOS-based firmware it is best to do it inside a task and use “vTaskDelay” to let other tasks execute until the connection is established (assuming that makes sense).

## Remote GUI Setup

Once “unity\_not\_ready” returns zero, it means MCUnity has transitioned out of the “init” state. It’s now possible to send GUI setup operations to the application. Those have been centralized in a firmware-specific function that has been passed to MCUnity. This function must be called exclusively through MCUnity, so it “knows it happened”.

Do this by calling “unity\_setup” (no argument, no return value). Among other things, this function will call the firmware’s custom GUI setup function.

Once this function returns, the MCUnity application is ready to interact with the MCUnity library and the firmware. MCUnity is in “update” mode.

## Update the Remote GUI

TO DO: INDICATE HOW TO PERFORM A REMOTE GUI UPDATE

Updates go both ways, but use two very different processes:

User input on the Unity application is sent to the firmware which makes it effective. This takes the form of update operation packets which are processed asynchronously (as received) by MCUnity’s UDP packet parser.

However, the MCUnity library is not capable of monitoring each variable registered with the remote GUI to send back update operations when one changes. This would require too much processing power.

Instead, MCUnity relies on the **firmware developer** to explicitly trigger remote GUI updates.

The exact placement of these update operations in a firmware depend entirely on that firmware, of course, but optimal placement follows simple, logical rules:

* If the GUI is never updated, it’s little more than an input device. This could be perfectly fine in some projects, for example if the impact of changing a variable from the GUI is observable through other means, like an actuator’s motion, an LED or a display driven by the MCU.
* If the GUI is updated too often, it steals processing power from the firmware’s true function. It may also generate too much network traffic. There’s no point updating a GUI:
  + More often than the refresh rate of the display that GUI is rendered on.
  + When the variables displayed by the GUI don’t change.

Thus, optimal placement is a trade-off. The goal should be to provide the human user with a reasonably responsive GUI without penalizing firmware performance.

A simple, good approach can be to trigger a GUI update from a FreeRTOS task so that it executes at a fixed frame-rate. This can be improved by adding a simple flag (a global variable) the firmware can set to indicate that a GUI update is necessary. This flag can be tested by the GUI update task and then cleared.

# Design Justification

## Centralization of setup operations

There are two possible situations that a firmware designer may want to account for:

* The **application** may already be running when the **firmware** starts running.
* The **firmware** may already be running when the **application** starts running.

For example, the device running the application may crash while the firmware is still running and the user may want to resume operation without resetting the MCU. Likewise, the firmware may crash and require the MCU be reset, but this shouldn’t also require exiting and restarting the application.

To help support these cases, the MCUnity library (firmware side) must be able to send the exact same GUI setup operations at any point during the execution of the firmware. This is what creates the need to encapsulate and centralize the setup operations.