Controls

Updated 25 March 2020

This page details the control strategies for the MIT E-Vent. Other control strategies with increasing complexity may be implemented at developer discretion and with clinical input.

Notice: Any control strategy must fulfill the requirements described in **Key Ventilation Specifications**.

The goal of the high-level controller is to provide a controlled volume of air to the patient in a set amount of time. There are two control phases: the **inspiratory phase** and the **expiratory phase** (see Figure 1). There are three input parameters, referencing the **Key Ventilation Specifications**:

Parameters

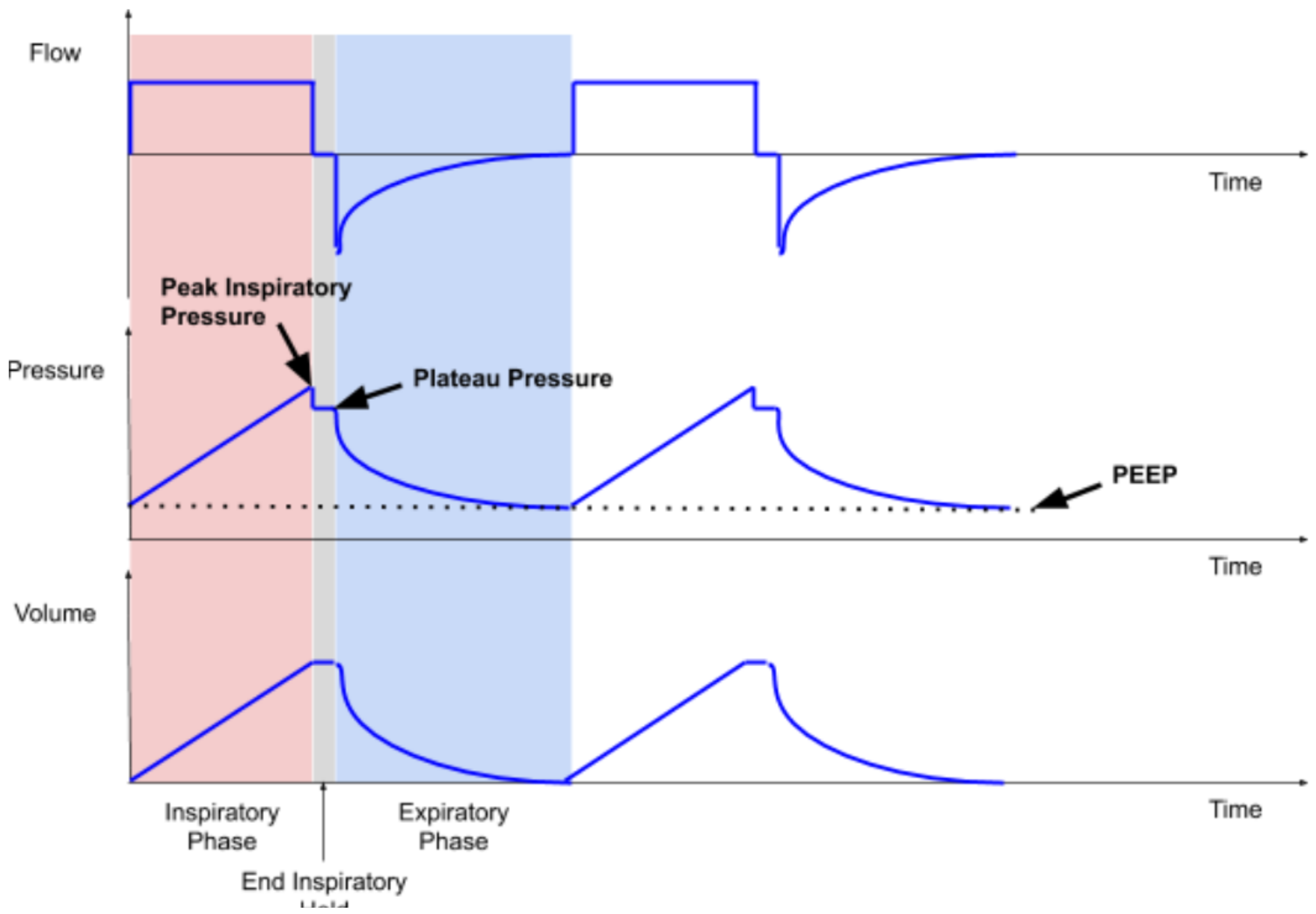
Tidal Volume (TV): The total volume of air to be delivered to the patient.

BPM: Breaths per minute, also called respiratory rate (RR). Typically varies between 8-30 BPM.

IE Ratio (IE): The ratio of the duration of the inhale to the duration of the exhale. For example, a 1:3 ratio means that the exhale phase lasts three times longer than the inhale phase. Typically varies between 1:1 to 1:3, with a maximum of 1:4 currently being observed in COVID-19 patients.

In addition to these inputs set by the clinician, the high-level controller uses two more inputs: the motor encoder position and the system pressure. Its job is then to translate all these inputs into the motor commands the low-level controller needs: desired motor speed and position.

Note that because our device does not directly measure volume, the tidal volume (VT) input of our controller is specified as a percent of a full compression of the Ambu bag instead of Liters. The percent (%) of bag compression from 0 – 100% maps to the encoder pulses that correspond to how far the fingers of the device move towards or away from each other and this determines the volume of air delivered.



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Hold

Figure 1 – Flow, Pressure, and Volume profiles for volume-control ventilation over 2 breath cycles; PEEP is illustrated on the Pressure plot. Image courtesy AK.

Our controller converts the three inputs into four parameters:

Period (T): The length of time (in seconds) of an inhale/exhale cycle.

$$T = 60 / BPM$$

T_{in}: The length of time (in seconds) of the inspiratory phase.

$$T_{in} = T / (1 + IE)$$

T_{ex}: The length of time (in seconds) of the expiratory phase.

$$T_{ex} = T - T_{in}$$

V_{in}: The rotation rate of the inspiratory phase (in pulses/second).

$$V_{in} = VT / T_{in}$$

In addition to these four parameters, there are three user-set parameters:

T_h: The amount of time (in seconds) to hold the compression at the end of the inhale for plateau pressure.

V_e: The velocity of the fingers in the expiratory phase (in pulses/second). Note that during exhalation, our device does not control flow rate out of the patient. This velocity is simply the velocity of the fingers opening and is not related to expiratory flow rate.

P_{max}: The maximum allowable pressure (set to 40 cmH20).

These six parameters are then used to control a state machine that switches between phases in the control loop (see Figure 2).

Time *t* is the amount of time spent in the current state.

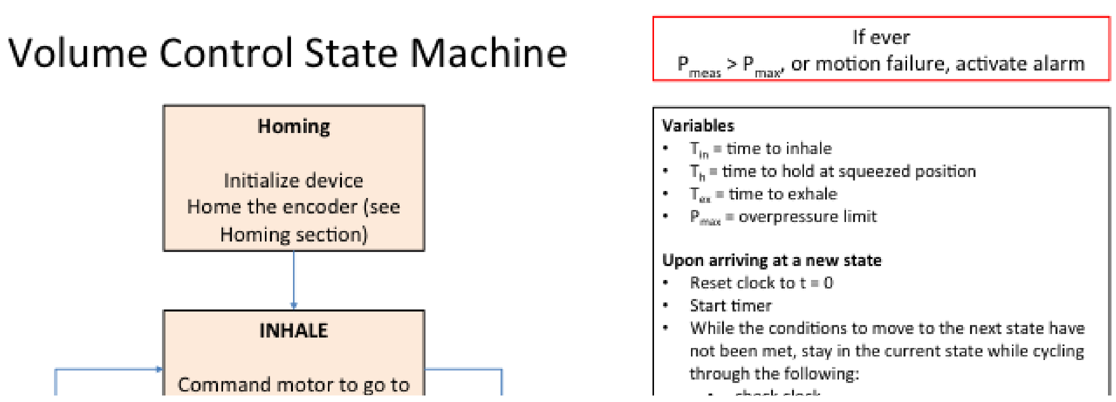
In addition to these three inputs, there are three measurable pressure parameters that must be taken into account (see Figure 2):

P_{ip}: Maximum pressure during inhale. We consider 40 cmH20 to be the upper pressure limit for safety. This also corresponds to the over-pressure release valve limit on some Ambu bags.

P_{plat}: The plateau pressure of the inhale. An important diagnostic number for clinicians.

PEEP: The residual pressure in the system after exhale. We do not directly control this value, but it is typically controlled manually via a PEEP valve on the Ambu Bag.

State Machine Summary



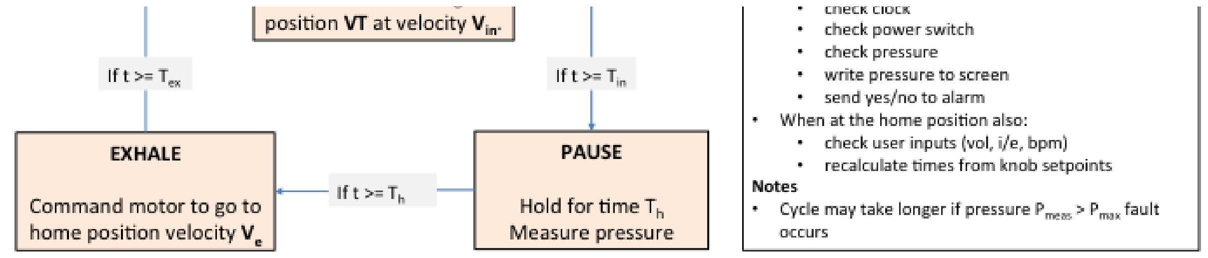


Figure 2 – State machine for controlling the breathing cycle.

During the setup phase, we initialize the program, start serial communication with the motor controller, and home the encoder.

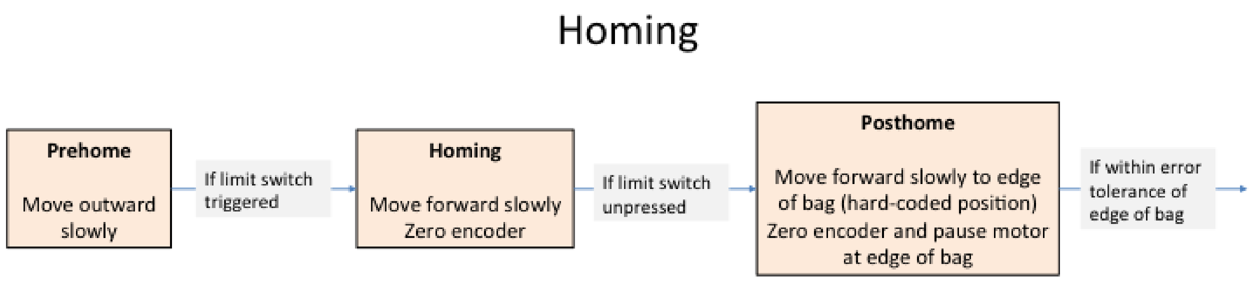


Figure 3 – We home the encoder using a limit switch.

In the inspiratory phase, we command the motor to go to position VT at velocity V_{in}. After T_{in} seconds, we switch to the pause state.

In the pause state, we hold for time T_h and measure the plateau pressure. We then switch to the expiratory phase.

In the expiratory phase, we command the motor to go to position 0 at velocity V_e. After time T_{ex}, we switch back to the inspiratory phase.

Plateau Pressure

Each time the arms close, we implement a 0.15 s pause before they open. This does not affect the I/E ratio, but it is necessary to hold the air into the patient. During this phase the airway pressure is measured and displayed. This indicates “plateau pressure” and will guide clinical decision making. This pressure will be displayed until the next cycle and update. Other pressures are less important but can be addressed in a more complicated control strategy.

Alarms Functions

Caution – Not yet implemented. Not all failure modes have been explored yet, so this document will be continuously updated as new faults are found.

All alarms must simply, concisely, and clearly alert the clinician of the type of fault, so that the clinician can decide how to proceed. For example, a mechanical fault requires a different clinical response than a patient who stops breathing on assist mode.

There are several different failure modes in volume control, which require different responses. For example, a compression may cause a lung overpressure fault, or the position setpoint may not be able to be reached.

So far, Volume Control faults include overpressure in the lungs, motor unable to reach desired position, and pressure not increasing when bag is squeezed. This is not a complete list.

In the Assist Control mode, the alarm will also sound whenever a breath is not activated by the patient and the system’s timer kicks in to command a breath. Additionally, if pressure does not change when the bag is squeezed, an alarm sounds.

Other alarm conditions will be added. The main goal of all alarms should be to concisely and unambiguously alert a technician that manual intervention is needed. The system should also inform the clinician of the cause of the fault, so that they can act accordingly.

Work in Progress

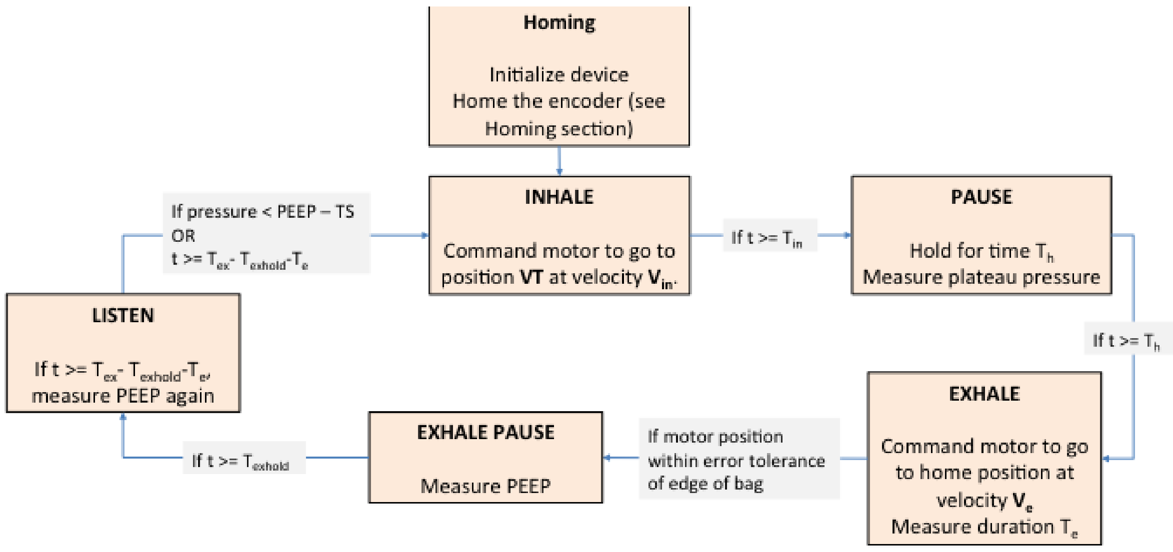


Figure 3 – Assist Control

Assist Control differs from regular volume control in that the Exhale state is split into 3 states. In the first Exhale state, the fingers move to their home position at the edge of the bag. In the second state, Exhale Pause, the fingers pause for a short time and measure the PEEP. In the third state, Listen, we wait either for the patient's own inhalation to trigger the Inhale state, or we wait for a set amount of time (like in normal Volume Control) and then trigger the Inhale state automatically.