

# MoULDyS User Guide

## Introduction

The tool `MoULDyS` is based on the following paper:

[Offline and Online Monitoring of Scattered Uncertain Logs Using Uncertain Linear Dynamical Systems.](#)

Bineet Ghosh, Étienne André.

In: Formal Techniques for Distributed Objects, Components, and Systems (FORTE) 2022.

Here, we will discuss how to perform the following:

- **Introduction to Logs.** This section will provide a brief introduction to the types of logs, with examples, that are currently supported by `MoULDyS`. We currently support logs represented as intervals and zonotopes.
- **Offline Monitoring.** Here, we provide a step wise guide on how to encode a dynamics and perform offline monitoring of a given log.
- **Online Monitoring.** Next, we will discuss the steps to perform online monitoring, given the actual behavior of the system.
- **Compare Online and Offline Monitoring.** In this section we will discuss steps to compare online and offline monitoring.
- **Generating Logs (Optional).** This optional section will provide a step wise guide to synthesize random logs of a system from a given initial set.

## Introduction to Logs

The logs are required to be stored at `/my/location/MoULDyS/data/`. We currently support logs represented as intervals and zonotopes. The log file must use the extension `.mlog`.

### Logs as Intervals

The format of the log is as follows:

```
<time_step>: <interval>
```

Following is an example log file:

```
4: [[1,2],[2,3]]
5: [[2,3],[5,6]]
```

Each line in the log file represents the log at a given time step. For instance, `4: [[1,2],[2,3]]` implies the behavior of the system is given by the interval `[[1,2],[2,3]]` at time step `4`.

# Logs as Zonotopes

The format of the log is as follows:

```
<time_step>: <center_of_zonotope>; <generator_of_zonotope>
```

Following is an example log file:

```
4: [0,0]; [[1,0],[0,1]]
5: [0,0]; [[1.2,0.1],[0.2,1.2]]
```

Each line in the log file represents the log at a given time step. For instance, 4: [0,0]; [[1,0],[0,1]] implies the behavior of the system is given by the zonotope with center [0,0] and generator [[1,0],[0,1]].

## Offline Monitoring

Consider the following toy dynamics for which we want to perform offline monitoring:

$$x[t+1] = Ax[t] + Bu[t];$$

where:

$$A = \begin{bmatrix} 1 & c \\ 0 & 1 \end{bmatrix},$$

$$B = \begin{bmatrix} d \\ 0.01 \end{bmatrix},$$

$c \in 0.1 \pm 1\%$ ,  $d \in 0.01 \pm 1\%$ , and  $\forall_t u[t] \in [-0.1, 0.1]$ .

### Step 0: Set the project path, and import MoULDyS engine.

```
import os, sys
PROJECT_ROOT = os.environ['MNTR_ROOT_DIR']
sys.path.append(PROJECT_ROOT) # Set the project path

from lib.MoULDySEngine import * # Importing all the functionalities of MoULDyS.
```

### Step 1: Encode the dynamics.

```
def toyEgOffline():
    A=np.array(
        [
            [1, 0.1],
            [0, 1]
        ]
    )
    B=np.array(
        [
            [0.01],
            [0.01]
        ]
    )
```

## Step 2: Define the mode of the dynamics.

- Use `.` for continuous time systems (Note: `MoULDyS` will discretize).
- Use `+` for discrete time systems.

```
mode='+'
```

## Optional: Set discretization parameter, if the mode is continuous.

```
h=0.01 # This step is not needed for this example. However, having this, wouldn't
have any impact in this example.
```

## Step 3: Encode the uncertainties in the dynamics.

The uncertainties in the dynamics are as follows:

- $c \in 0.1 \pm 1\%$ . If matrices  $A$  and  $B$  are augmented together, this uncertainty would be at cell  $(0, 1)$  of the augmented matrix. To encode an uncertainty of 1%, we use the following syntax:  $[0.99, 1.01]$ .
- $d \in 0.1 \pm 1\%$ . If matrices  $A$  and  $B$  are augmented together, this uncertainty would be at cell  $(0, 2)$  of the augmented matrix.
  - The augmented dynamics is given below. Note that `MoULDyS` augments the dynamics as follows, internally, before performing monitoring.

$$\circ \quad augment(A, B) = \Lambda = \begin{bmatrix} 1 & c & d \\ 0 & 1 & 0.01 \\ 0 & 0 & 1 \end{bmatrix}.$$

- Therefore, the dynamics  $x[t + 1] = Ax[t] + Bu[t]$  can be rewritten as follows:
  - $z[t + 1] = \Lambda z[t]$
  - Note that the input  $u[t] \in \mathcal{U}$ , for all  $t$ , is treated as a state variable in the augmented dynamics.

## Step 4: Encode the unsafe set.

Let the unsafe behavior be as follows:

- `state_variable_0 >=200` AND
- `state_variable_0 <=-200`

Unsafe sets can be encoded as intervals

```
unsafe1=[(-np.inf, -200), (-np.inf, np.inf), (-np.inf, np.inf)]
unsafe2=[(200, np.inf), (-np.inf, np.inf), (-np.inf, np.inf)]
unsafeList=[unsafe1, unsafe2]
```

## Step 5: Instantiate the MoULDyS engine.

```
mEngine=MoULDyS(A, B, Er, mode, unsafeList, h) # Note: In this example, h is optional.
```

## Step 6: Perform offline monitoring

Let the log be given in the file [/my/location/MoULDyS/data/toyEg\\_1\\_interval](#) (Note: Don't use .mlog extension).

```
logFname='toyEg_1_interval'
tp='interval' # Use tp='zonotope', if the log file is represented in zonotope.
reachSets=mEngine.offlineMonitorLogFile(logFname, tp)
```

## Step 7: Visualize the results of monitoring

Following is the color coding of the generated figures:

- Blue: Reachable sets from offline monitoring.
- Black: Logs generated by the offline monitoring.

```
T=2000 # Time step upto which we want to visualize
th1=0 # State variable that is to be visualized
vizCov=5 # Percentage of reachable sets to be visualized. Note: Visualizing all
reachable sets is expensive.
#Note: Visualization takes time!
mEngine.vizMonitorLogFile(reachSets, logFname, tp, T, th1, "toyEg_monitor", vizCoverage
=vizCov)
```

## Final Code Snippet

```
import os, sys
PROJECT_ROOT = os.environ['MNTR_ROOT_DIR']
sys.path.append(PROJECT_ROOT) # Set the project path

from lib.MoULDySEngine import * # Importing all the functionalities of MoULDyS.

def toyEgOffline():
    ##### Step 1 #####
    A=np.array(
```

```

[
[1, 0.1],
[0, 1]
]
)
B=np.array(
[
[0.01],
[0.01]
]
)
)
##### Step 2 #####
mode='+'

##### Optional #####
h=0.01

##### Step 3 #####
Er={
(0,1): [0.99,1.01], # Encoding c
(0,2): [0.99,1.01], # Encoding d
}

##### Step 4 #####
unsafe1=[(-np.inf, -200), (-np.inf, np.inf), (-np.inf, np.inf)]
unsafe2=[(200, np.inf), (-np.inf, np.inf), (-np.inf, np.inf)]
unsafeList=[unsafe1, unsafe2]

##### Step 5 #####
mEngine=MoULDyS(A,B,Er,mode,unsafeList,h) # Note: In this example, h is
optional.

##### Step 6 #####
logFname='toyEg_1_interval'
tp='interval' # Use tp='zonotope', if the log file is represented in
zonotope.
reachSets=mEngine.offlineMonitorLogFile(logFname, tp)

##### Step 7 #####

T=2000 # Time step upto which we want to visualize
th1=0 # State variable that is to be visualized
vizCov=5 # Percentage of reachable sets to be visualized.
#Note: Visualization takes time!

mEngine.vizMonitorLogFile(reachSets, logFname, tp, T, th1, "toyEg_monitor", vizCoverag
e=vizCov)

toyEgOffline()

```

This snippet can be found in

</my/location/MoULDyS/src/tutorial/TutorialOfflineMonitoring.py>.

# Online Monitoring

Similar to offline monitoring, we provide the steps to perform online monitoring of the toy example dynamics, given its actual behavior.

## Step 1: Perform steps 0-3 as offline monitoring.

```
import os, sys
PROJECT_ROOT = os.environ['MNTR_ROOT_DIR']
sys.path.append(PROJECT_ROOT) # Set the project path

from lib.MoULDySEngine import * # Importing all the functionalities of MoULDyS.

def toyEgOffline():
    ##### Step 1 #####
    A=np.array(
    [
    [1, 0.1],
    [0, 1]
    ]
    )
    B=np.array(
    [
    [0.01],
    [0.01]
    ]
    )
    ##### Step 2 #####
    mode='+ '

    ##### Optional #####
    h=0.01

    ##### Step 3 #####
    Er={
    (0,1): [0.99,1.01], # Encoding c
    (0,2): [0.99,1.01], # Encoding d
    }
```

## Step 4: Encode the unsafe set (let's use a different one from offline).

Let the unsafe behavior be as follows:

- `state_variable_0 >=20` AND
- `state_variable_0 <=-20`

```
unsafe1=[(-np.inf, -20), (-np.inf, np.inf), (-np.inf, np.inf)]
unsafe2=[(20, np.inf), (-np.inf, np.inf), (-np.inf, np.inf)]
unsafeList=[unsafe1, unsafe2]
```

## Step 5: Instantiate the MoULDyS engine.

```
mEngine=MoULDyS(A,B,Er,mode,unsafeList,h) # Note: In this example, h is optional.
```

## Step 6: Perform online monitoring.

- Let the actual behavior be given in file [/my/location/MoULDyS/data/toyEg\\_1\\_interval](#) (Note: Don't use `.mbeh` extension)
- The actual behavior type can either be interval or zonotope.

```
logFname='toyEg_1_interval'  
tp='interval' # Use tp='zonotope', if the log file is represented in zonotope.  
(reachSets, logs)=mEngine.onlineMonitorBehFile(logFname,tp)
```

## Step 7: Visualize the results of monitoring.

Following is the color coding of the generated figures:

- Black: Represents logs.
- Blue: Represents reachable sets.
- Red: Unsafe region.

```
T=2000 # Time step upto which we want to visualize  
th1=0 # State variable that is to be visualized  
vizCov=5 # Percentage of reachable sets to be visualized. Note: Visualizing all  
reachable sets is expensive.  
#Note: Visualization takes time!  
mEngine.vizMonitor(reachSets, logs, tp, T, th1, "toyEg_monitor", vizCoverage=vizCov)
```

## Final Code Snippet

```
import os, sys  
PROJECT_ROOT = os.environ['MNTR_ROOT_DIR']  
sys.path.append(PROJECT_ROOT) # Set the project path  
  
from lib.MoULDySEngine import * # Importing all the functionalities of MoULDyS.  
  
def toyEgOnline():  
    ##### Step 1-3 #####  
    A=np.array(  
        [  
            [1, 0.1],  
            [0, 1]  
        ]  
    )  
    B=np.array(  
        [  
            [0.01],  
            [0.01]  
        ]  
    )  
    mode='+'
```

```

h=0.01 # This step is not needed for this example.

##### Step 3 #####
'''
Step 3: Encode the uncertainties in the dynamics (i.e, c and d)
'''
Er={
(0,1): [0.99,1.01], # Encoding c
(0,2): [0.99,1.01], # Encoding d
}

##### Step 4 #####
'''
Step 4: Encode the unsafe set.
Let the unsafe behavior be as follows:
* state_variable_0 >=20 AND
* state_variable_0 <=-20
Unsafe sets can be encoded as intervals
'''
unsafe1=[(-np.inf, -20), (-np.inf, np.inf), (-np.inf, np.inf)]
unsafe2=[(20, np.inf), (-np.inf, np.inf), (-np.inf, np.inf)]
unsafeList=[unsafe1,unsafe2]

##### Step 5 #####
mEngine=MoULDyS(A,B,Er,mode,unsafeList,h) # Note: In this example, h is
optional.

##### Step 6 #####
logFname='toyEg_1_interval'
tp='interval' # Use tp='zonotope', if the log file is represented in
zonotope.
(reachSets, logs)=mEngine.onlineMonitorBehFile(logFname, tp)

##### Step 7 #####
T=2000 # Time step upto which we want to visualize
th1=0 # State variable that is to be visualized
vizCov=5 # Percentage of reachable sets to be visualized. Note: Visualizing
all reachable sets is expensive.
#Note: Visualization takes time!

mEngine.vizMonitor(reachSets, logs, tp, T, th1, "toyEg_monitor", vizCoverage=vizCov)

toyEgOnline()

```

This snippet can be found in

</my/location/MoULDyS/src/tutorial/TutorialOnlineMonitoring.py>.

## Compare Online and Offline Monitoring



## Step 1: Perform steps 0-5 as online monitoring.

```
import os, sys
PROJECT_ROOT = os.environ['MNTR_ROOT_DIR']
sys.path.append(PROJECT_ROOT) # Set the project path

from lib.MoULDySEngine import * # Importing all the functionalities of MoULDyS.

def toyEgOnline():
    ##### Step 1-3 #####
    A=np.array(
    [
    [1, 0.1],
    [0, 1]
    ]
    )
    B=np.array(
    [
    [0.01],
    [0.01]
    ]
    )
    mode='+'
    h=0.01 # This step is not needed for this example.

    ##### Step 3 #####
    '''
    Step 3: Encode the uncertainties in the dynamics (i.e, c and d)
    '''
    Er={
    (0,1): [0.99,1.01], # Encoding c
    (0,2): [0.99,1.01], # Encoding d
    }

    ##### Step 4 #####
    '''
    Step 4: Encode the unsafe set.
    Let the unsafe behavior be as follows:
    * state_variable_0 >=20 AND
    * state_variable_0 <=-20
    Unsafe sets can be encoded as intervals
    '''
    unsafe1=[(-np.inf, -20), (-np.inf, np.inf), (-np.inf, np.inf)]
    unsafe2=[(20, np.inf), (-np.inf, np.inf), (-np.inf, np.inf)]
    unsafeList=[unsafe1, unsafe2]

    ##### Step 5 #####
    mEngine=MoULDyS(A,B,Er,mode,unsafeList,h) # Note: In this example, h is
    optional.
```

## Step 2: Perform both offline and online monitoring.

```
logFname='toyEg_1_interval'
tp='interval' # Use tp='zonotope', if the log file is represented in zonotope.
reachSets=mEngine.offlineMonitorLogFile(logFname,tp)
(reachSetsOnline, logsOnline)=mEngine.onlineMonitorBehFile(logFname,tp)
```

## Step 3: Visualize both the results from online and offline monitoring.

Following is the color coding of the generated figures:

- Blue: Reachable sets from online monitoring.
- Black: Logs generated by the online monitoring.
- Green: Reachable sets from offline monitoring.
- Magenta: Logs provided to the offline monitoring.
- Red: Unsafe region.

```
T=2000 # Time step upto which we want to visualize
th1=0 # State variable that is to be visualized
vizCov=5 # Percentage of reachable sets to be visualized. Note: Visualizing all
reachable sets is expensive.
mEngine.vizCompMonitorLogFile(reachSets, logFname, reachSetsOnline, logsOnline, tp, T,
th1, "viz_test", vizCov)
```

## Final Code Snippet

```
import os, sys
PROJECT_ROOT = os.environ['MNTR_ROOT_DIR']
sys.path.append(PROJECT_ROOT) # Set the project path

from lib.MoULDySEngine import * # Importing all the functionalities of MoULDyS.

def toyEgCompare():
    ##### Step 1-2 #####
    A=np.array(
        [
            [1, 0.1],
            [0, 1]
        ]
    )
    B=np.array(
        [
            [0.01],
            [0.01]
        ]
    )
    mode='+'
    h=0.01 # This step is not needed for this example.

    ##### Step 3 #####
    '''
    Step 3: Encode the uncertainties in the dynamics (i.e, c and d)
    '''
```

```

Er={
  (0,1): [0.99,1.01], # Encoding c
  (0,2): [0.99,1.01], # Encoding d
}

##### Step 4 #####
'''
Step 4: Encode the unsafe set.
Let the unsafe behavior be as follows:
* state_variable_0 >=20 AND
* state_variable_0 <=-20
Unsafe sets can be encoded as intervals
'''

unsafe1=[(-np.inf, -20), (-np.inf, np.inf), (-np.inf, np.inf)]
unsafe2=[(20, np.inf), (-np.inf, np.inf), (-np.inf, np.inf)]
unsafeList=[unsafe1, unsafe2]

##### Step 5 #####
mEngine=MoULDyS(A,B,Er,mode,unsafeList,h) # Note: In this example, h is
optional.

##### Step 6 #####
logFname='toyEg_1_interval'
tp='interval' # Use tp='zonotope', if the log file is represented in
zonotope.
reachSets=mEngine.offlineMonitorLogFile(logFname, tp)
(reachSetsOnline, logsOnline)=mEngine.onlineMonitorBehFile(logFname, tp)

##### Step 7 #####
T=2000 # Time step upto which we want to visualize
th1=0 # State variable that is to be visualized
vizCov=5 # Percentage of reachable sets to be visualized. Note: Visualizing
all reachable sets is expensive.

mEngine.vizCompMonitorLogFile(reachSets, logFname, reachSetsOnline, logsOnline, tp, T
, th1, "viz_test", vizCov)

```

This snippet can be found in

</my/location/MoULDyS/src/tutorial/TutorialCompareMonitoring.py>.

## Generate Logs (Optional)

This optional section discusses how to generate logs.

### Step 1: Perform steps 0-3 as offline monitoring

```

import os, sys
PROJECT_ROOT = os.environ['MNTR_ROOT_DIR']
sys.path.append(PROJECT_ROOT) # Set the project path

from lib.MoULDySEngine import * # Importing all the functionalities of MoULDyS.

def toyEgOffline():
    ##### Step 1 #####
    A=np.array(

```

```

[
[1, 0.1],
[0, 1]
]
)
B=np.array(
[
[0.01],
[0.01]
]
)
)
##### Step 2 #####
mode='+'

##### Optional #####
h=0.01

##### Step 3 #####
Er={
(0,1): [0.99,1.01], # Encoding c
(0,2): [0.99,1.01], # Encoding d
}

```

## Step 2: Instantiate the MoULDyS engine.

```
mEngine=MoULDyS(A,B,Er,mode,unsafeList,h) # Note: In this example, h is optional.
```

## Step 3: Generate random logs

```

initialSet=[(0,0),(0,0),(-0.1,0.1)] # Initial Set, represented as an interval
pr=1 # Probability of logging
fname='toyEg'
T=2000 # Time upto which logs are generated
tp='interval' # Use tp='zonotope' for creating logs with zonotopes
(log,actualBehavior)=mEngine.genLogFile(initialSet,T,fname,tp,pr)

```

## Final Code Snippet

```

import os,sys
PROJECT_ROOT = os.environ['MNTR_ROOT_DIR']
sys.path.append(PROJECT_ROOT) # Set the project path

from lib.MoULDySEngine import * # Importing all the functionalities of MoULDyS.

def toyEgOffline():
    ##### Step 1 #####
    A=np.array(
    [
    [1, 0.1],
    [0, 1]
    ]
    )
    B=np.array(

```

```

[
[0.01],
[0.01]
]
)
##### Step 2 #####
mode='+'

##### Optional #####
h=0.01

##### Step 3 #####
Er={
(0,1): [0.99,1.01], # Encoding c
(0,2): [0.99,1.01], # Encoding d
}
mEngine=MoULDyS(A,B,Er,mode,unsafeList,h) # Note: In this example, h is
optional.
initialSet=[(0,0),(0,0),(-0.1,0.1)] # Initial Set, represented as an interval
pr=1 # Probability of logging
fname='toyEg'
T=2000 # Time upto which logs are generated
tp='interval' # Use tp='zonotope' for creating logs with zonotopes
(log,actualBehavior)=mEngine.genLogFile(initialSet,T,fname,tp,pr)

```

This will generate logs file (extension `.mlog`) and behavior file (extension `.mbeh`) in </my/location/data/>.