Workshop on Space Microelectronics, WoSM
(conjunction with 4th Conference on Aerospace Robotics, CARO4)
Zielona Góra, July 8th, 2022

HLS approach for robust control algorithm implementation in FPGA

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AGENDA

1. Control algorithm
2. Modeling and simulation
3. FPGA implementation of algorithms
4. Results
5. Conclusions

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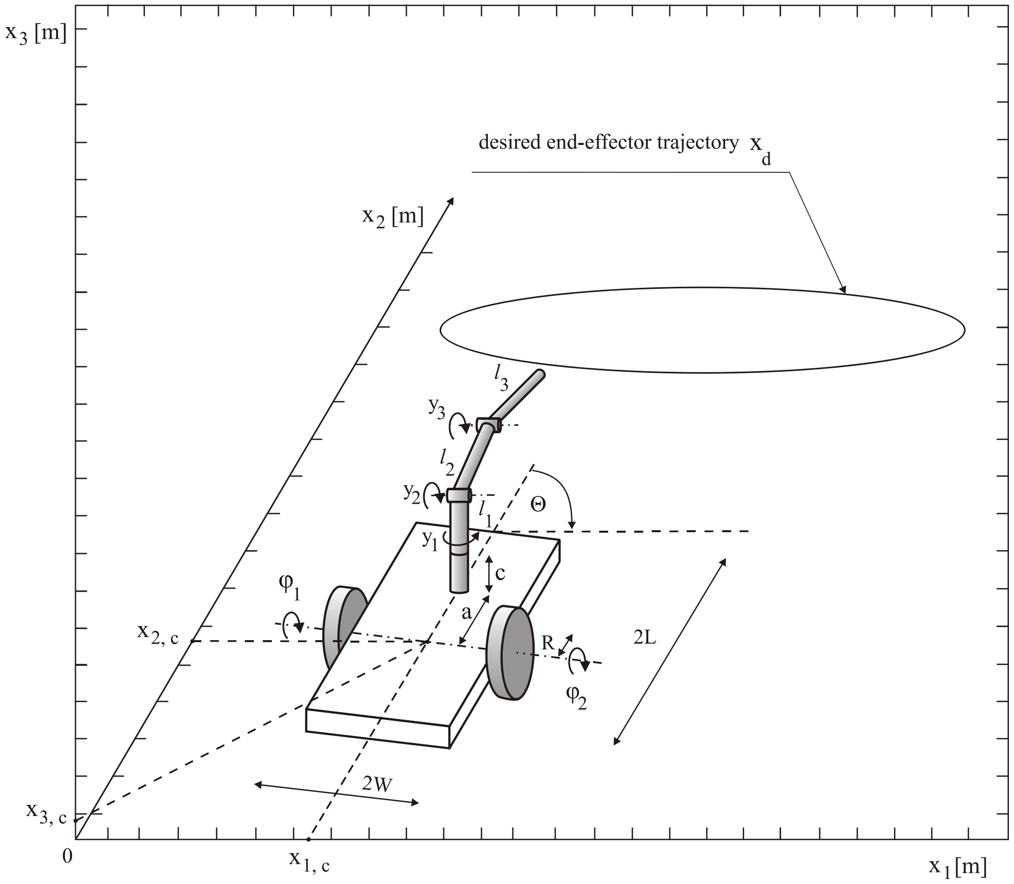
ROBUST CONTROL ALGORITHM

The problem to be solved:

$$q = \left(x_{1,c}\,,\, x_{2,c}\,,\, x_{3,c}\,, \varphi_1, \varphi_2, y_1, y_2, y_3\right)^T$$



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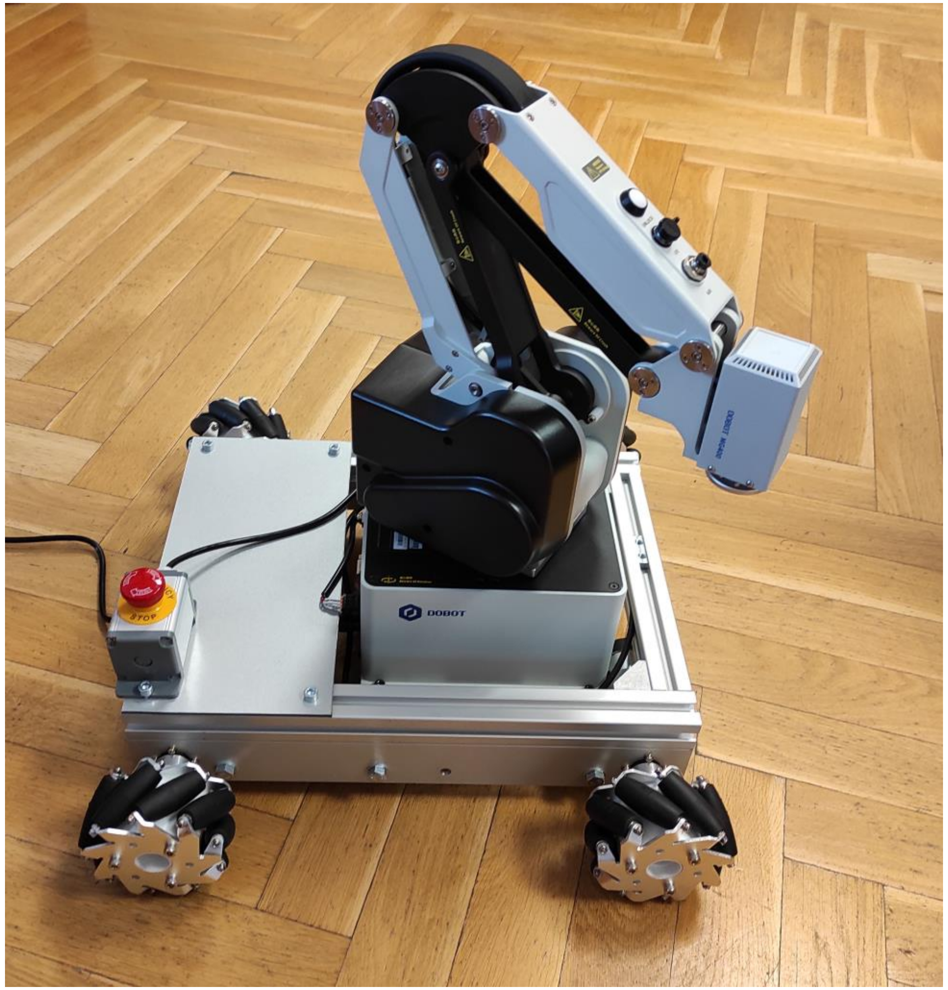
MOBILE *SPACE* ROBOT



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ROBUST CONTROL OF SPACE MANIPULATORS INPUT DATA

- Modeling
  - differential equations, Runge Kutta method
  - Matlab and C languages

- Simulation
  - Matlab
  - C-based program

- Implementation
  - Microprocessor system (e.g., Raspeberry)
  - C-based program

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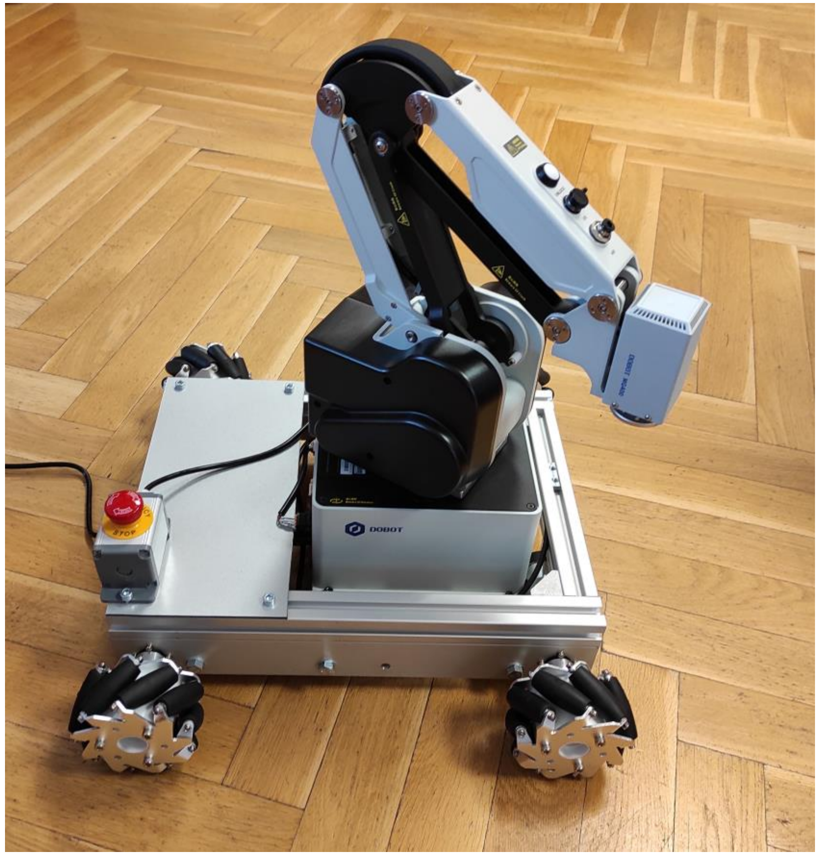
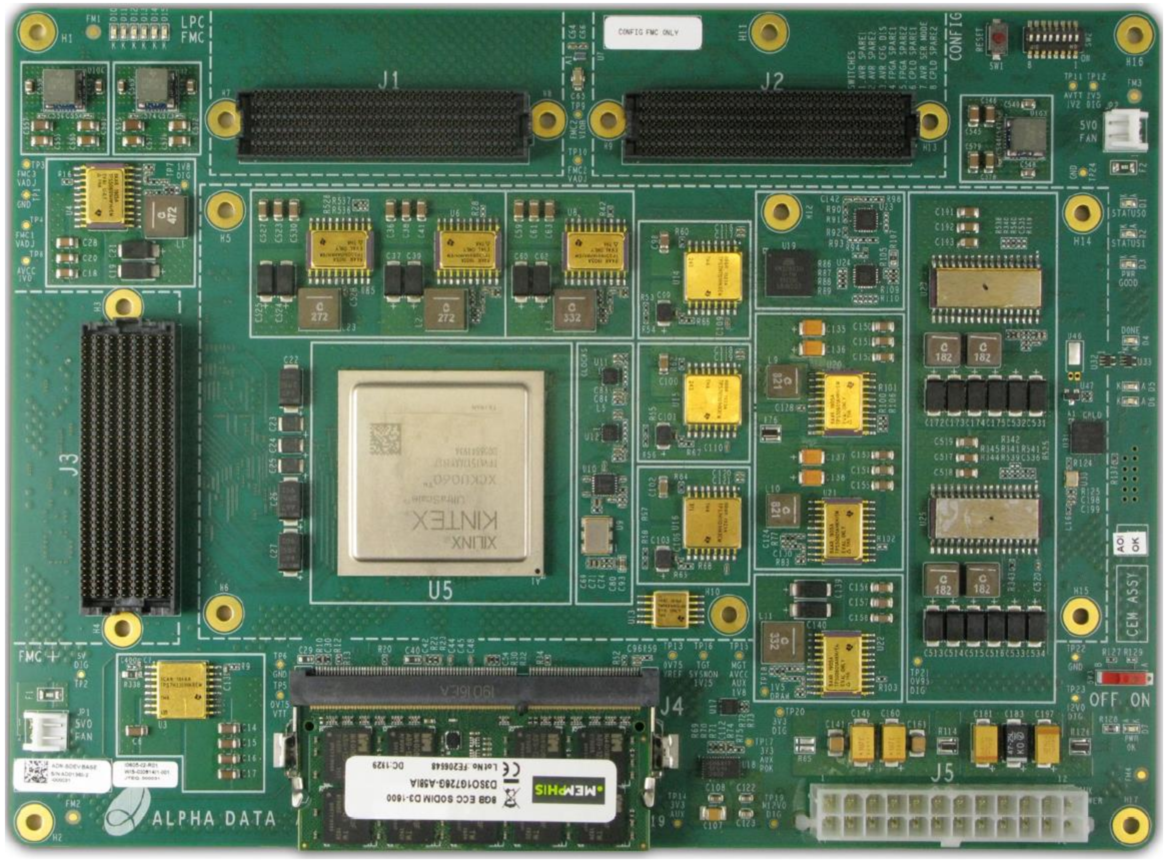
MOBILE *SPACE* ROBOT – FPGA-based Controller

(Xilinx Kintex Ultrascale XQRKU060 Space-Grade FPGA, e.g., ADA-SDEV-KIT2)





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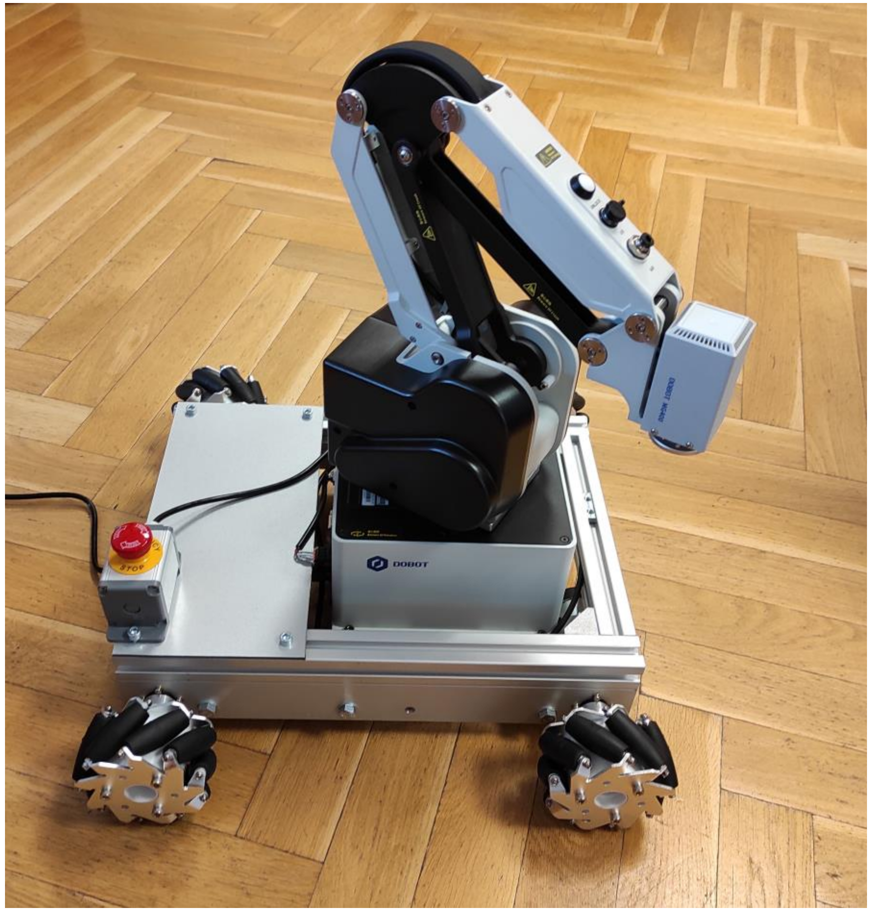
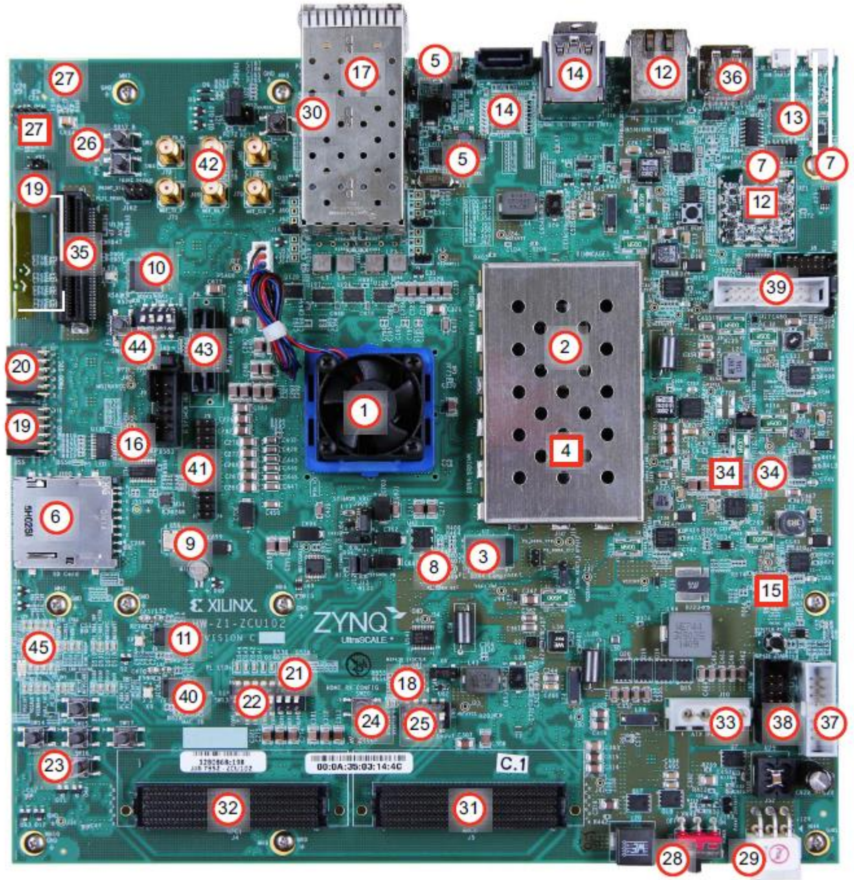
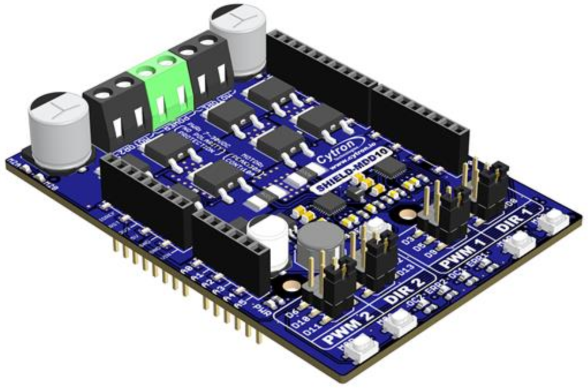
MOBILE *SPACE* ROBOT – XILINX FPGA ZCU102







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MOBILE *SPACE* ROBOT

C MODEL, DIFFERENTIA EQUATION SOLVER PROBLEM

```
#define N_ELEMENTS 19                  // State vector size
#define N_DATA     13                  // Data vector (XA) size
#define N_VSTU     11                  // 8 thrusters + 3 joints

// xn - current time [sec]
// % XA  - is the state vector
// %             x[0]  -  x-position of the satellite's center of mass [m]
// %             x[1]  -  y-position of the satellite's center of mass [m]
// %             x[2]  -  satellite orientation [rad]
// %             x[3]  -  angular position of the first  joint [rad]
// %             x[4]  -  angular position of the second joint [rad]
// %             x[5]  -  angular position of the third  joint [rad]
// %             x[6]  -  the first derivative of x[0] [m/sec]
// %             x[7]  -  the first derivative of x[1] [m/sec]
// %             x[8]  -  the first derivative of x[2] [rad/sec]
// %             x[9]  -  the first derivative of x[3] [rad/sec]
// %             x[10] -  the first derivative of x[4] [rad/sec]
// %             x[11] -  the first derivative of x[5] [rad/sec]
// %             x[12] -  mass of the system [kg]
```

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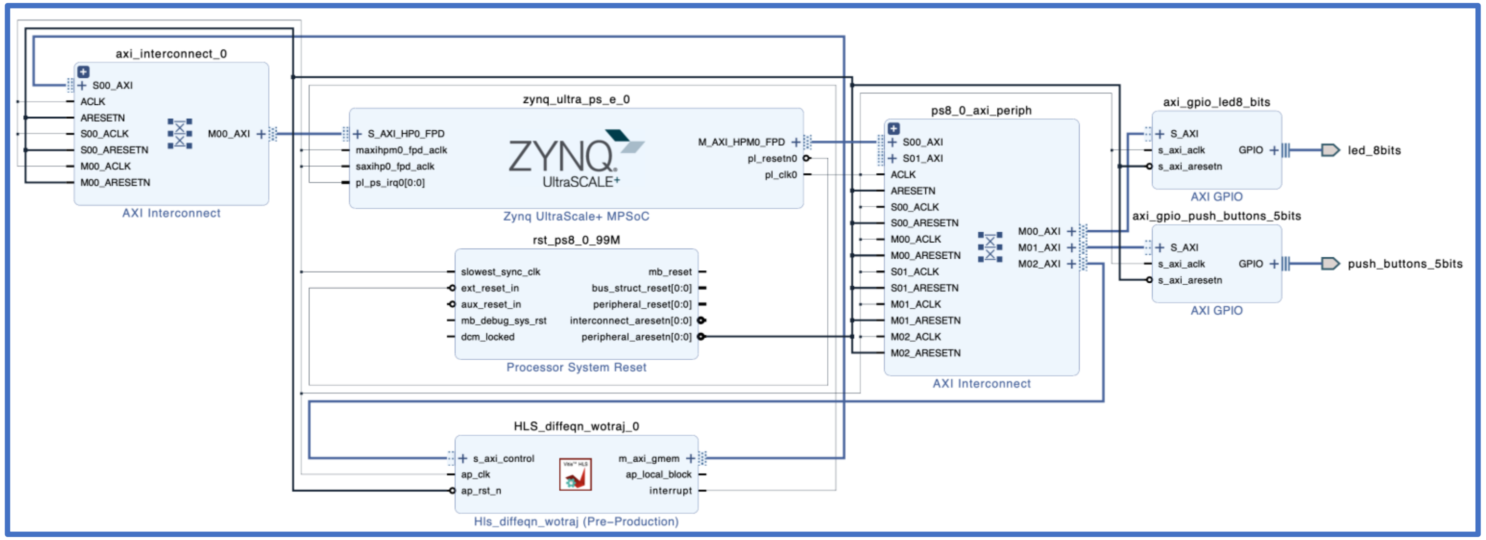
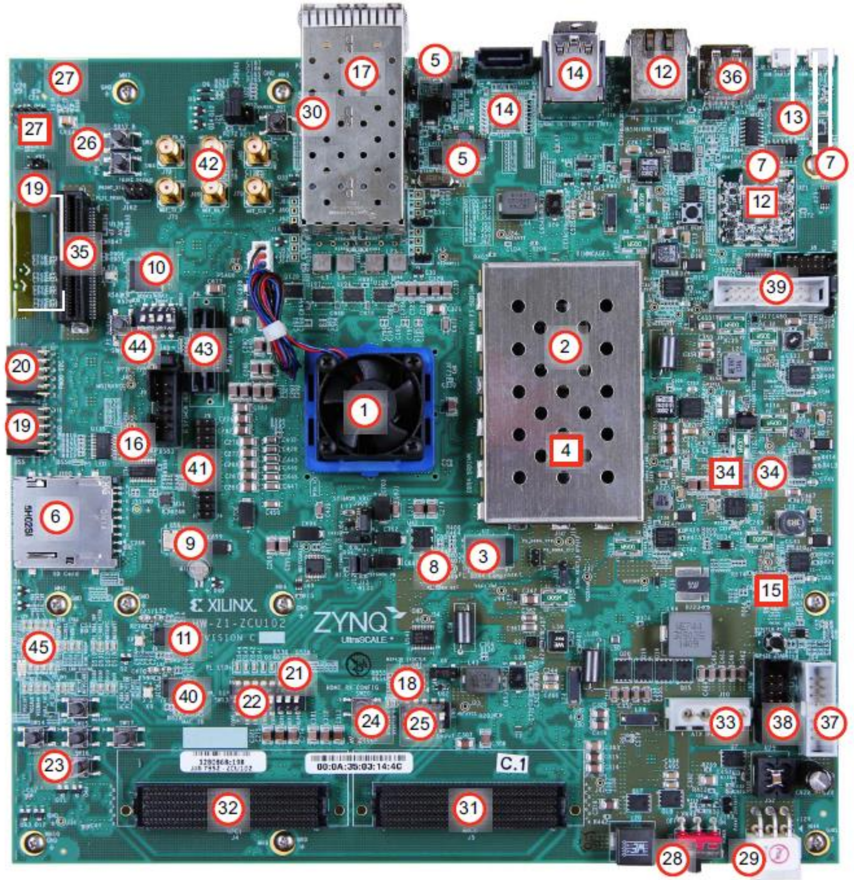
FPGA IDEA OF IMPLEMENTATION

```c
/**
 * @brief Discrete robot model with controller
 *
 * @param t (input) current time
 * @param x (input) manipulator state (x)
 * @param dx (output) state increase (dx)
 * @param vstu (output) control vector
 * @param xd (input) desired position
 * @param xpd (input) desired first derivative of position
 * @param xppd (input) desired secound derivative of position
 * @return void
 */

void diffeqn_wotraj (double t, float *x, float *dx, float *vstu, float *xd, float *xpd, float *xppd)
{
    float fq[6 * 1], J[6 * 6], Mm[6 * 6], Cm[6 * 1], Gm[6 * 1],
    Bm[6* 11], Dm[6 * 1];
    //float xd[6 * 1], xpd[6 * 1], xppd[6 * 1];

    kinematics_c(t, x, fq, J);

    dynamics0_c(t, x, Mm, Cm, Gm, Bm, Dm);

    //trajectory_c(t, xd, xpd, xppd);

    controller_c(t, x, dx, fq, J, Mm, Cm, Gm, Bm, Dm, xd, xpd, xppd, vstu);

} //diffeqn
```





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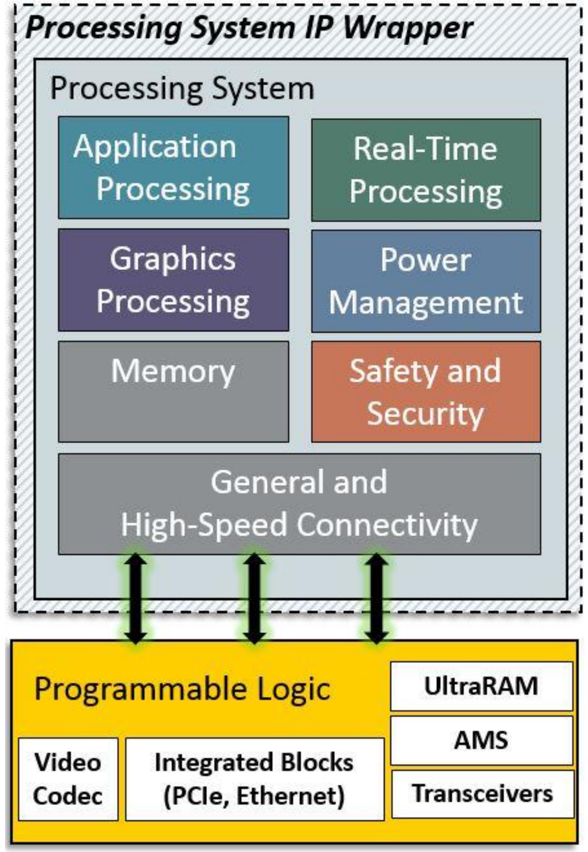
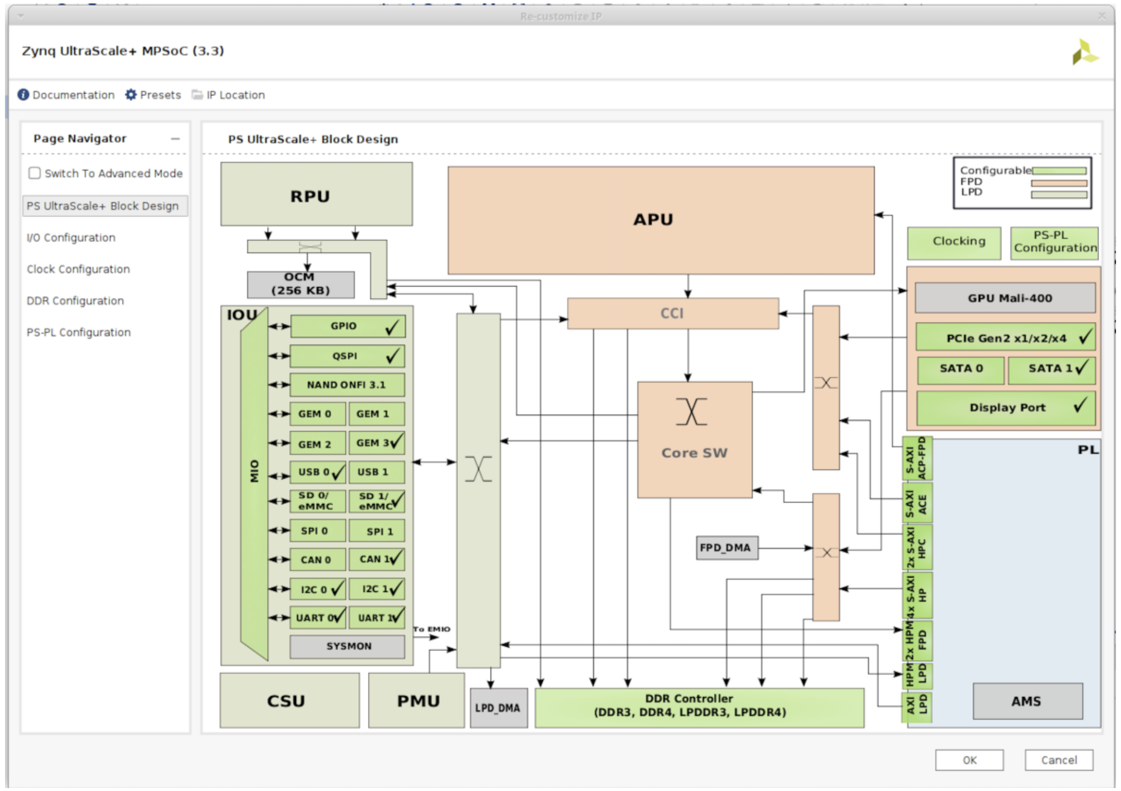
HIGH LEVEL SYNTHESIS APPROACH
PROCESSOR SYSTEM + PROGRAMMABLE LOGIC





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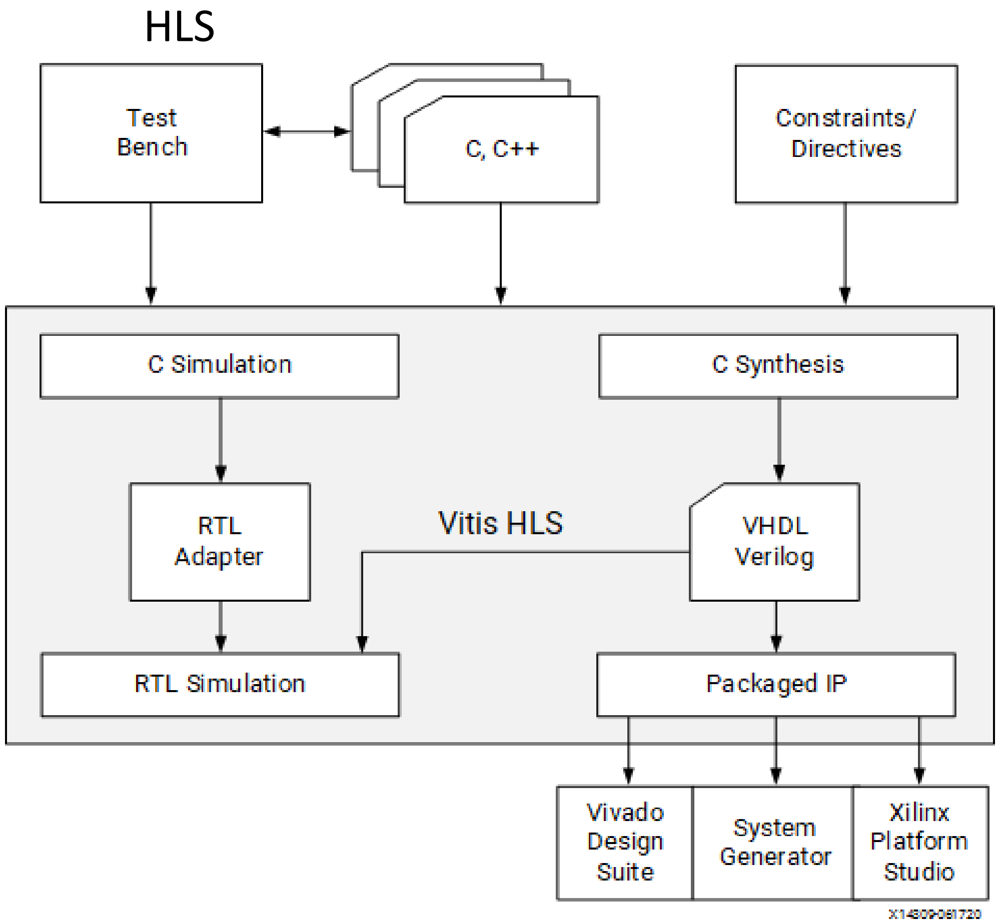
HIGH LEVEL SYNTHESIS APPROACH

HLS DESIGN FLOW




```c
/**
 * @brief Discrete robot model with controller
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 * @param t (input) current time
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 * @return void
 */

void diffeqn_wotraj (double t, float *x, float *dx, float *vstu, float *xd, float *xpd, float *xppd)
{
    float fq[6 * 1], J[6 * 6], Mm[6 * 6], Cm[6 * 1], Gm[6 * 1],
    Bm[6* 11], Dm[6 * 1];
    //float xd[6 * 1], xpd[6 * 1], xppd[6 * 1];

    kinematics_c(t, x, fq, J);

    dynamics0_c(t, x, Mm, Cm, Gm, Bm, Dm);

    //trajectory_c(t, xd, xpd, xppd);

    controller_c(t, x, dx, fq, J, Mm, Cm, Gm, Bm, Dm, xd, xpd, xppd, vstu);

} //diffeqn
```

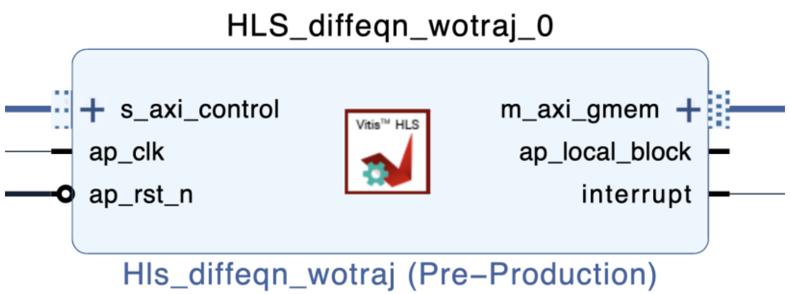

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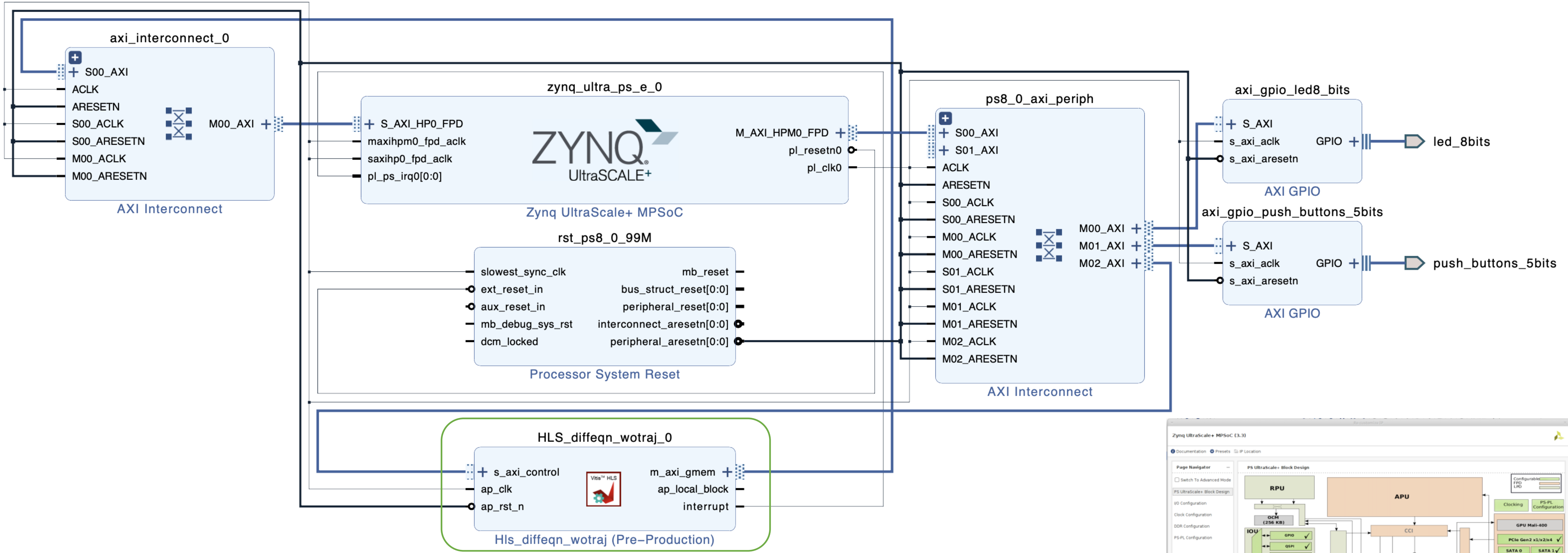
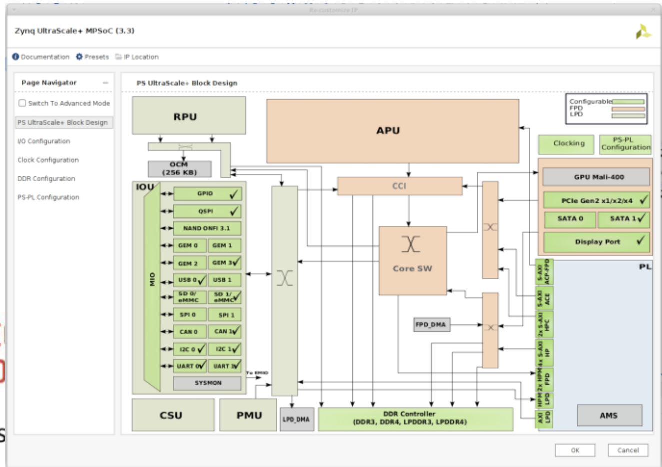
PROCESSOR SYSTEM + PROGRAMMABLE LOGIC





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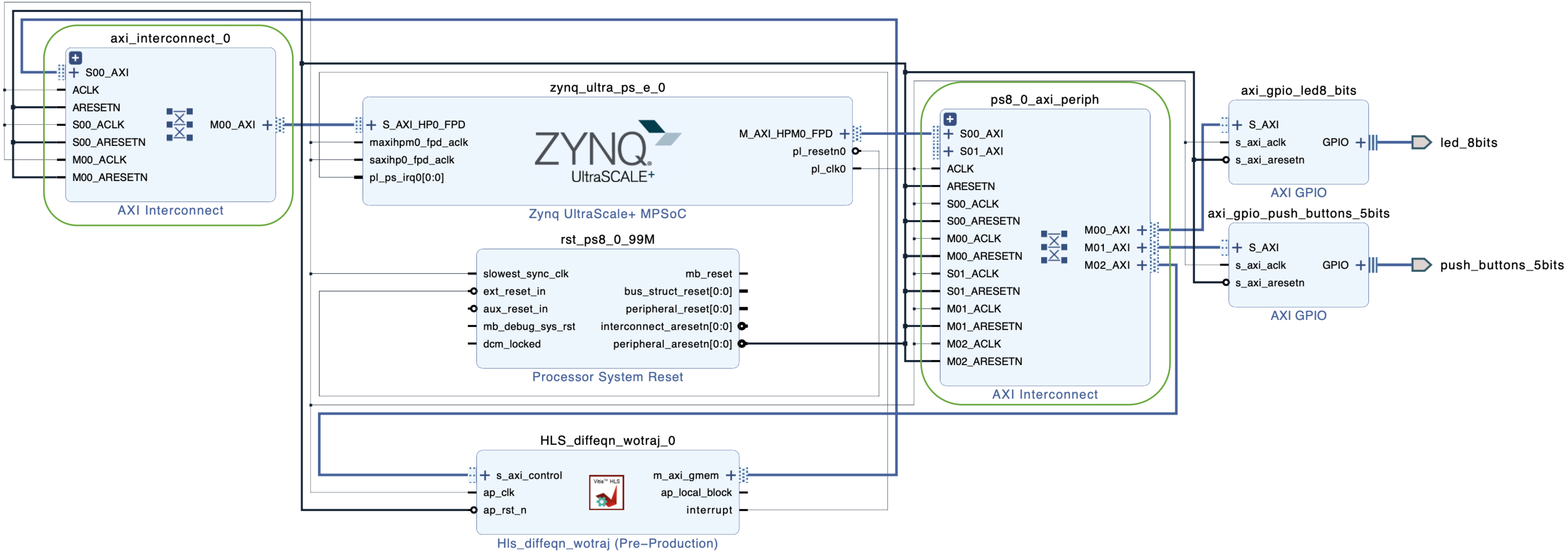
HIGH LEVEL SYNTHESIS APPROACHAXI CONTROL AND AXI GLOBAL MEMORY



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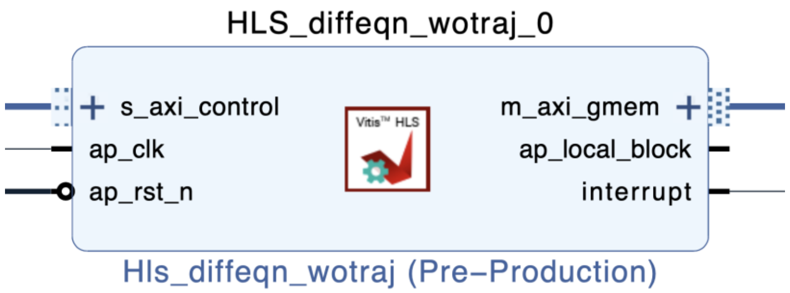
HIGH LEVEL SYNTHESIS APPROACH
HLS CODDING FLOW – INTERFACE

```c
/**
 * @brief Discrete robot model with controller
 *
 * @param t (input) current time
 * @param x (input) manipulator state (x)
 * @param dx (output) state increase (dx)
 * @param vstu (output) control vector
 * @param xd (input) desired position
 * @param xpd (input) desired first derivative of position
 * @param xppd (input) desired secound derivative of position
 * @return void
 */

void diffeqn_wotraj (double t, float *x, float *dx, float *vstu, float *xd, float *xpd, float *xppd)
{
    float fq[6 * 1], J[6 * 6], Mm[6 * 6], Cm[6 * 1], Gm[6 * 1],
    Bm[6* 11], Dm[6 * 1];
    //float xd[6 * 1], xpd[6 * 1], xppd[6 * 1];

    kinematics_c(t, x, fq, J);

    dynamics0_c(t, x, Mm, Cm, Gm, Bm, Dm);

    //trajectory_c(t, xd, xpd, xppd);

    controller_c(t, x, dx, fq, J, Mm, Cm, Gm, Bm, Dm, xd, xpd, xppd, vstu);

} //diffeqn
```

```c
extern "C" void HLS_diffeqn_wotraj(const double *t, const float *x, float *dx,
        float *vstu, float const *xd, float const *xpd, const float *xppd) {
#pragma HLS INTERFACE m_axi port = t depth = T_SIZE offset=slave bundle=gmem
#pragma HLS INTERFACE m_axi port = x depth = X_SIZE offset=slave bundle=gmem
#pragma HLS INTERFACE m_axi port = dx depth = X_SIZE offset=slave bundle=gmem
#pragma HLS INTERFACE m_axi port = vstu depth = VSTU_SIZE offset=slave bundle=gmem
#pragma HLS INTERFACE m_axi port = xd depth = XD_SIZE offset=slave bundle=gmem
#pragma HLS INTERFACE m_axi port = xpd depth = XD_SIZE offset=slave bundle=gmem
#pragma HLS INTERFACE m_axi port = xppd depth = XD_SIZE offset=slave bundle=gmem
#pragma HLS INTERFACE s_axilite port=return
```



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HIGH LEVEL SYNTHESIS APPROACH
HLS CODDING FLOW – DATAFLOW

```c
/**
 * @brief Discrete robot model with controller
 *
 * @param t (input) current time
 * @param x (input) manipulator state (x)
 * @param dx (output) state increase (dx)
 * @param vstu (output) control vector
 * @param xd (input) desired position
 * @param xpd (input) desired first derivative of position
 * @param xppd (input) desired secound derivative of position
 * @return void
 */

void diffeqn_wotraj (double t, float *x, float *dx, float *vstu, float *xd, float *xpd, float *xppd)
{
    float fq[6 * 1], J[6 * 6], Mm[6 * 6], Cm[6 * 1], Gm[6 * 1],
    Bm[6* 11], Dm[6 * 1];
    //float xd[6 * 1], xpd[6 * 1], xppd[6 * 1];

    kinematics_c(t, x, fq, J);

    dynamics0_c(t, x, Mm, Cm, Gm, Bm, Dm);

    //trajectory_c(t, xd, xpd, xppd);

    controller_c(t, x, dx, fq, J, Mm, Cm, Gm, Bm, Dm, xd, xpd, xppd, vstu);

} //diffeqn
```

```c
double buf_t;
float buf_x[X_SIZE];
float buf_dx[X_SIZE];
float buf_vstu[VSTU_SIZE];
float buf_xd[XD_SIZE];
float buf_xpd[XD_SIZE];
float buf_xppd[XD_SIZE];

float fq[XSS_SIZE * 1], J[XSS_SIZE * XSS_SIZE], Mm[XSS_SIZE * XSS_SIZE],
        Cm[XSS_SIZE * 1], Gm[XSS_SIZE * 1], Bm[XSS_SIZE * VSTU_SIZE],
        Dm[XSS_SIZE * 1];

//INPUT buffers
memcpy(buf_x, x, X_SIZE*sizeof(float)); //input
//memcpy(buf_dx, dx, X_SIZE*sizeof(float)); //output
//memcpy(buf_vstu, vstu, VSTU_SIZE*sizeof(float)); //output
memcpy(buf_xd, xd, XD_SIZE*sizeof(float)); //input
memcpy(buf_xpd, xpd, XD_SIZE*sizeof(float)); //input
memcpy(buf_xppd, xppd, XD_SIZE*sizeof(float)); //input

//FUNCTIONS
kinematics_c(buf_t, buf_x, fq, J);
dynamics0_c(buf_t, buf_x, Mm, Cm, Gm, Bm, Dm);
//trajectory_c(buf_t, buf_xd, buf_xpd, buf_xppd);
controller_c(buf_t, buf_x, buf_dx, fq, J, Mm, Cm, Gm, Bm, Dm, buf_xd, buf_xpd, buf_xppd, buf_vstu);

//OUTPUT buffers
//memcpy(x, buf_x, X_SIZE*sizeof(float)); //input
memcpy(dx, buf_dx, X_SIZE*sizeof(float)); //output
memcpy(vstu, buf_vstu, VSTU_SIZE*sizeof(float)); //output
//memcpy(xd, buf_xd, XD_SIZE*sizeof(float)); //input
//memcpy(xpd, buf_xpd, XD_SIZE*sizeof(float)); //input
//memcpy(xppd, buf_xppd, XD_SIZE*sizeof(float)); //input
```

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HIGH LEVEL SYNTHESIS APPROACH
HLS DIRECT METHOD PERFORMANCE

```
void diffeqn_wotraj (double t, float *x, float *dx, float *vstu, float *xd, float *xpd, float *xppd)
{
    float fq[6 * 1], J[6 * 6], Mm[6 * 6], Cm[6 * 1], Gm[6 * 1],
    Bm[6* 11], Dm[6 * 1];
    //float xd[6 * 1], xpd[6 * 1], xppd[6 * 1];

    kinematics_c(t, x, fq, J);

    dynamics0_c(t, x, Mm, Cm, Gm, Bm, Dm);

    //trajectory_c(t, xd, xpd, xppd);

    controller_c(t, x, dx, fq, J, Mm, Cm, Gm, Bm, Dm, xd, xpd, xppd, vstu);

} //diffeqn
```

Modules & Loops	Issue Type	Violation Type	Distance	Slack	Latency(cycles)	Latency(ns)	Iteration Latency	Interval	Trip Count	Pipelined	BRAM	DSP	FF	LUT	URAM
HLS_diffeqn_wotraj				-0.50	12826	1.280E5	-	12827	-	no	230	1770	90654	172655	0
HLS_diffeqn_wotraj_Pipeline_1				-	29	290.000	-	29	-	no	0	0	218	371	0
HLS_diffeqn_wotraj_Pipeline_2				-	16	160.000	-	16	-	no	0	0	214	368	0
kinematics_c				-	85	850.000	-	85	-	no	0	0	1991	1042	0
HLS_diffeqn_wotraj_Pipeline_3				-	16	160.000	-	16	-	no	0	0	214	368	0
dynamics0_c	II Violation			-0.37	894	8.940E3	-	894	-	no	46	686	43720	63867	0
HLS_diffeqn_wotraj_Pipeline_4				-	16	160.000	-	16	-	no	0	0	214	368	0
controller_c	II Violation			-0.50	11743	1.170E5	-	11743	-	no	107	274	22640	48394	0
HLS_diffeqn_wotraj_Pipeline_5				-	27	270.000	-	27	-	no	0	0	154	366	0
HLS_diffeqn_wotraj_Pipeline_6				-	19	190.000	-	19	-	no	0	0	153	366	0

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HIGH LEVEL SYNTHESIS APPROACH
HLS DIRECT METHOD PERFORMANCE ANALYSIS

Modules & Loops	Issue Type	Violation Type	Distance	Slack	Latency(cycles)	Latency(ns)	Iteration Latency	Interval	Trip Count	Pipelined	BRAM	DSP	FF	LUT	URAM
HLS_diffeqn_wotraj				-0.50	12826	1.280E5	-	12827	-	no	230	1770	90654	172655	0
HLS_diffeqn_wotraj_Pipeline_1				-	29	290.000	-	29	-	no	0	0	218	371	0
HLS_diffeqn_wotraj_Pipeline_2				-	16	160.000	-	16	-	no	0	0	214	368	0
kinematics_c				-	85	850.000	-	85	-	no	0	0	1991	1042	0
kinematics_c_Pipeline_1				-	8	80.000	-	8	-	no	0	0	5	45	0
kinematics_c_Pipeline_2				-	38	380.000	-	38	-	no	0	0	8	50	0
sin_or_cos_double_s				-	29	290.000	-	29	-	no	8	86	1618	5657	0
sin_or_cos_double_s				-	29	290.000	-	29	-	no	8	86	1618	5657	0
sin_or_cos_double_s				-	29	290.000	-	29	-	no	8	86	1618	5657	0
sin_or_cos_double_s				-	29	290.000	-	29	-	no	8	86	1618	5657	0
sin_or_cos_double_s				-	29	290.000	-	29	-	no	8	86	1618	5657	0
sin_or_cos_double_s				-	29	290.000	-	29	-	no	8	86	1618	5657	0
sin_or_cos_double_s				-	29	290.000	-	29	-	no	8	86	1618	5657	0
sin_or_cos_double_s				-	29	290.000	-	29	-	no	8	86	1618	5657	0
HLS_diffeqn_wotraj_Pipeline_3				-	16	160.000	-	16	-	no	0	0	214	368	0
dynamics0_c	II Violation			-0.37	894	8.940E3	-	894	-	no	46	686	43720	63867	0
HLS_diffeqn_wotraj_Pipeline_4				-	16	160.000	-	16	-	no	0	0	214	368	0
controller_c	II Violation			-0.50	11743	1.170E5	-	11743	-	no	107	274	22640	48394	0
HLS_diffeqn_wotraj_Pipeline_5				-	27	270.000	-	27	-	no	0	0	154	366	0
HLS_diffeqn_wotraj_Pipeline_6				-	19	190.000	-	19	-	no	0	0	153	366	0

HIGH LEVEL SYNTHESIS APPROACH

HLS DIRECT METHOD PERFORMANCE ANALYSIS

Modules & Loops	Issue Type	Violation Type	Distance	Slack	Latency(cycles)	Latency(ns)	Iteration Latency	Interval	Trip Count	Pipelined	BRAM	DSP	FF	LUT	URAM
HLS_diffeqn_wotraj				-0.50	12826	1.280E5	-	12827	-	no	230	1770	90654	172655	0
HLS_diffeqn_wotraj_Pipeline_1				-	29	290.000	-	29	-	no	0	0	218	371	0
HLS_diffeqn_wotraj_Pipeline_2				-	16	160.000	-	16	-	no	0	0	214	368	0
kinematics_c				-	85	850.000	-	85	-	no	0	0	1991	1042	0
HLS_diffeqn_wotraj_Pipeline_3				-	16	160.000	-	16	-	no	0	0	214	368	0
dynamics0_c				-0.37	894	8.940E3	-	894	-	no	46	686	43720	63867	0
dynamics0_c_Pipeline_1				-	8	80.000	-	8	-	no	0	0	5	45	0
dynamics0_c_Pipeline_2				-	8	80.000	-	8	-	no	0	0	5	45	0
dynamics0_c_Pipeline_3				-	68	680.000	-	68	-	no	0	0	9	51	0
sin_or_cos_double_s				-	29	290.000	-	29	-	no	8	86	1618	5657	0
sin_or_cos_double_s				-	29	290.000	-	29	-	no	8	86	1618	5657	0
sin_or_cos_double_s				-	29	290.000	-	29	-	no	8	86	1618	5657	0
dynamics0_c_Pipeline_4				-	14	140.000	-	14	-	no	0	0	6	48	0
sin_or_cos_double_s				-	29	290.000	-	29	-	no	8	86	1618	5657	0
dynamics0_c_Pipeline_5				-	14	140.000	-	14	-	no	0	0	6	48	0
sin_or_cos_double_s				-	29	290.000	-	29	-	no	8	86	1618	5657	0
sin_or_cos_double_s				-	29	290.000	-	29	-	no	8	86	1618	5657	0
dynamics0_c_Pipeline_6				-	9	90.000	-	9	-	no	0	0	5	45	0
sin_or_cos_double_s				-	29	290.000	-	29	-	no	8	86	1618	5657	0
sin_or_cos_double_s				-	29	290.000	-	29	-	no	8	86	1618	5657	0
sin_or_cos_double_s				-	29	290.000	-	29	-	no	8	86	1618	5657	0
multMMc				-	42	420.000	-	42	-	no	0	3	285	343	0
multMMc				-	42	420.000	-	42	-	no	0	3	285	343	0
multMMc				-	42	420.000	-	42	-	no	0	3	285	343	0
multMMc				-	42	420.000	-	42	-	no	0	3	285	343	0
multMMc				-	42	420.000	-	42	-	no	0	3	285	343	0
sin_or_cos_double_s				-	29	290.000	-	29	-	no	8	86	1618	5657	0
sin_or_cos_double_s				-	29	290.000	-	29	-	no	8	86	1618	5657	0
transp				-	14	140.000	-	14	-	no	0	0	16	179	0
multMM_1	II Violation			-	224	2.240E3	-	224	-	no	0	5	684	825	0
multMM_1	II Violation			-	224	2.240E3	-	224	-	no	0	5	684	825	0
sumMM				-	43	430.000	-	43	-	no	0	2	418	422	0
sumMM				-	43	430.000	-	43	-	no	0	2	418	422	0

HIGH LEVEL SYNTHESIS APPROACH
HLS DIRECT METHOD PERFORMANCE ANALYSIS

Modules & Loops	Issue Type	Violation Type	Distance	Slack	Latency(cycles)	Latency(ns)	Iteration Latency	Interval	Trip Count	Pipelined	BRAM	DSP	FF	LUT	URAM
HLS_diffeqn_wotraj				-0.50	12826	1.280E5	-	12827	-	no	230	1770	90654	172655	0
HLS_diffeqn_wotraj_Pipeline_1				-	29	290.000	-	29	-	no	0	0	218	371	0
HLS_diffeqn_wotraj_Pipeline_2				-	16	160.000	-	16	-	no	0	0	214	368	0
kinematics_c				-	85	850.000	-	85	-	no	0	0	1991	1042	0
HLS_diffeqn_wotraj_Pipeline_3				-	16	160.000	-	16	-	no	0	0	214	368	0
dynamics0_c	II Violation			-0.37	894	8.940E3	-	894	-	no	46	686	43720	63867	0
HLS_diffeqn_wotraj_Pipeline_4				-	16	160.000	-	16	-	no	0	0	214	368	0
controller_c				-0.50	11743	1.170E5	-	11743	-	no	107	274	22640	48394	0
inv6	II Violation			-	914	9.140E3	-	914	-	no	2	18	3135	3625	0
minMM				-	11	110.000	-	11	-	no	0	2	306	302	0
multMM_2	II Violation			-	169	1.690E3	-	169	-	no	0	5	516	572	0
controller_c_Pipeline_VITIS_LOOP_78_1_VITIS_LOOP_78_2				-	76	760.000	-	76	-	no	0	1	208	168	0
controller_c_Pipeline_VITIS_LOOP_39_1_VITIS_LOOP_39_2				-	71	710.000	-	71	-	no	0	1	51	168	0
multMM_6	II Violation			-	1199	1.199E4	-	1199	-	no	0	6	766	865	0
power				-	22	220.000	-	22	-	no	30	70	4019	11205	0
power				-	22	220.000	-	22	-	no	30	70	4019	11205	0
power				-	22	220.000	-	22	-	no	30	70	4019	11205	0
controller_c_Pipeline_VITIS_LOOP_78_1_VITIS_LOOP_78_23				-	43	430.000	-	43	-	no	0	0	191	208	0
multMM_5	II Violation			-	1196	1.196E4	-	1196	-	no	0	5	690	850	0
controller_c_Pipeline_VITIS_LOOP_39_1_VITIS_LOOP_39_24				-	38	380.000	-	38	-	no	0	0	21	202	0
controller_c_Pipeline_VITIS_LOOP_78_1_VITIS_LOOP_78_26				-	43	430.000	-	43	-	no	0	0	191	208	0
controller_c_Pipeline_VITIS_LOOP_39_1_VITIS_LOOP_39_28				-	38	380.000	-	38	-	no	0	0	21	202	0
multMM_4	II Violation			-	309	3.090E3	-	309	-	no	0	5	520	582	0
multMM_3	II Violation			-	259	2.590E3	-	259	-	no	0	5	519	561	0
controller_c_Pipeline_VITIS_LOOP_78_1_VITIS_LOOP_78_25				-	76	760.000	-	76	-	no	0	1	208	168	0
controller_c_Pipeline_VITIS_LOOP_39_1_VITIS_LOOP_39_27				-	71	710.000	-	71	-	no	0	1	51	168	0
HLS_diffeqn_wotraj_Pipeline_5				-	27	270.000	-	27	-	no	0	0	154	366	0
HLS_diffeqn_wotraj_Pipeline_6				-	19	190.000	-	19	-	no	0	0	153	366	0

TOP-DOWN, AND BOTTOM-UP APPROACH HLS_DIFFEQN_WOTRAJ CONCLUSIONS

- Acceleration is possible with lower latency than PC and ARM
- Tested by
    - PC (win, linux, macOS), ~1ms
    - ARM (linux): raspberry pi, ~10ms
    - ARM (bare metal): ZCU102, ~20ms
    - PS+PL (qemu on linux): ZCU102, ~300ms
    - PS+PL (bare metal): ZCU102 ~340us (~120us PL algorithm 100MHz)
- Speed up is possible by
    - Choose method of trigonometric function calculations
    - Matrix (add, sum, inv) operation pipelining another approach
    - Prestorage data in other form
    - FLOATING to FIXEDPOINT

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HIGH LEVEL SYNTHESIS APPROACH
NEW CHALANGE RUNGE-KUTTA ALGORITHM

```c
/**
 * @brief Discrete robot model r4k solver without controller
 * @brief and shared parameters (constants)
 *
 * @param t[in] current time
 * @param tnew[out] time after r4k step
 * @param x [in] manipulator state (x)
 * @param xnew[out] new manipulator state (x_new) after r4k
 * @param vstu [out] control vector XXX(to discuss, DJ: should be input!!!)
 * @param xd [in] desired position
 * @param xpd [in] desired first derivative of position
 * @param xppd [in] desired secound derivative of position
 * @param fq
 * @param J
 * @param Mm
 * @param Cm
 * @param Gm
 * @param Bm
 * @param Dm
 * @return void
 */
void diffeqn_f4k0_globaldata(double t, double tnew, double dt, float *x, float *xnew, float *vstu, float *xd,
        float *xpd, float *xppd, float *fq, float *J, float *Mm, float *Cm, float *Gm, float *Bm, float *Dm) {

    double buf_t;
    float f4k_x[X_SIZE];
    float f4k_x0[X_SIZE];
    float f4k_x1[X_SIZE];
    float f4k_x2[X_SIZE];
    float f4k_x3[X_SIZE];
    float f4k_dx0[X_SIZE];
    float f4k_dx1[X_SIZE];
    float f4k_dx2[X_SIZE];
    float f4k_dx3[X_SIZE];
    float f4k_xnew[X_SIZE];

    memcpy(f4k_x, x, X_SIZE*sizeof(float)); //input -- working only on local values!!!

    //1st (0) step:
    diffeqn_wotraj0_globaldata(t, f4k_x, f4k_dx0, vstu, xd, xpd, xppd, fq, J, Mm, Cm, Gm, Bm, Dm);
    for (int i=0;i<X_SIZE;i++) f4k_x1[i] = f4k_x[i]+dt*f4k_dx0[i];
    //2nd (1) step:
    diffeqn_wotraj0_globaldata((t+dt/2), f4k_x1, f4k_dx1, vstu, xd, xpd, xppd, fq, J, Mm, Cm, Gm, Bm, Dm);
    for (int i=0;i<X_SIZE;i++) f4k_x2[i] = f4k_x[i]+dt*f4k_dx1[i];
    //3rd (2) step:
    diffeqn_wotraj0_globaldata((t+dt/2), f4k_x2, f4k_dx2, vstu, xd, xpd, xppd, fq, J, Mm, Cm, Gm, Bm, Dm);
    for (int i=0;i<X_SIZE;i++) f4k_x3[i] = f4k_x[i]+dt*f4k_dx2[i];
    //4th (3) step:
    diffeqn_wotraj0_globaldata((t+dt), f4k_x3, f4k_dx3, vstu, xd, xpd, xppd, fq, J, Mm, Cm, Gm, Bm, Dm);
    //Runge-Kutta sum
    for (int i=0;i<X_SIZE;i++) f4k_xnew[i]=f4k_x[i]+dt*(f4k_dx0[i]+2.0*f4k_dx1[i]+2.0*f4k_dx2[i]+f4k_dx3[i])/6.0;

    memcpy(xnew,f4k_xnew, X_SIZE*sizeof(float)); //input -- working only on local values!!!
    tnew = t + dt;
```

- Optimalisation by
  - Matrix operation pipelining
  - One time trigonometric function computation
- Originally latency: 30 084 cycles
- Matrix loops: 12 826 cycles
- SIN/COS: 8761
- Function rearange: 7001

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Conclusions

1. Control algorithm was translated to low level languages
2. Simple **diffeqn_wotraj** study and proof of concept was performed with satisfying effects
3. Complex **diffeqn_f4k0** (4 times diffeqn_wotraj with sum) Runge Kutta was implemented successfully
4. TO DO

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